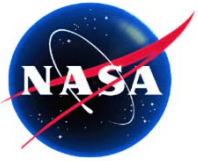


Temperature Oscillations in Loop Heat Pipes – A Revisit

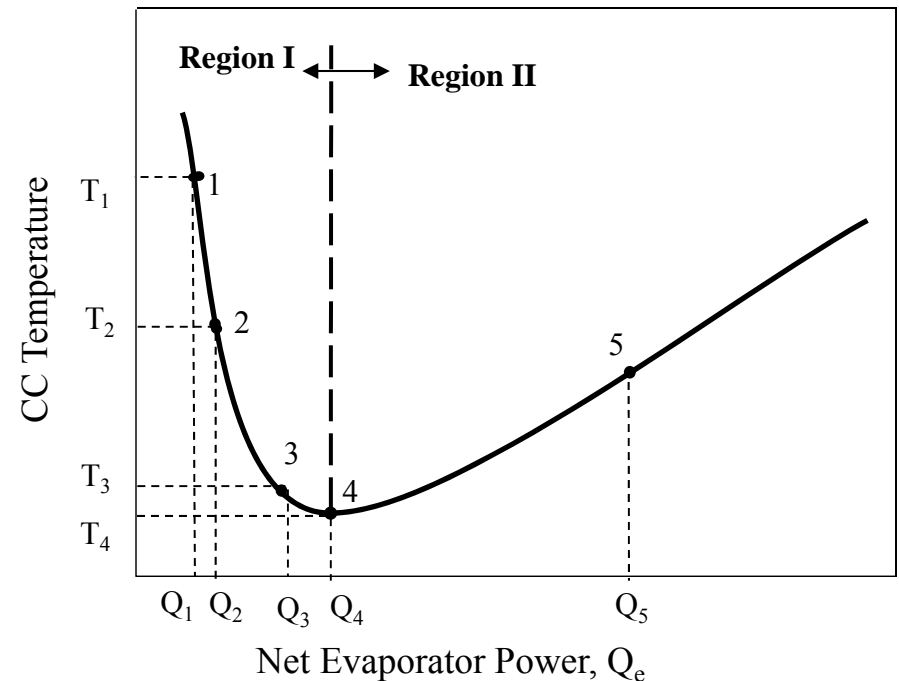
**Jentung Ku
NASA Goddard Space Flight Center
Greenbelt, Maryland**

**2018 Spacecraft Thermal Control Workshop
El Segundo, California, March 20-22, 2018**

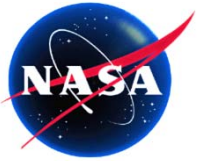


Outline

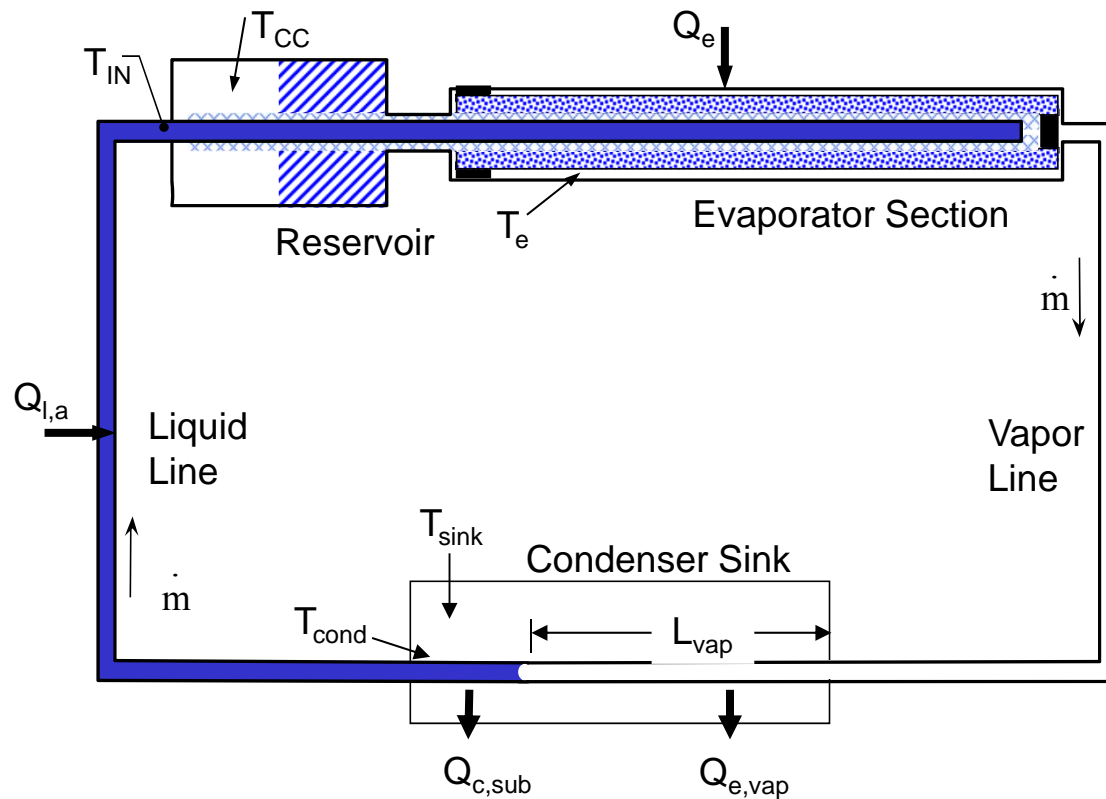
- **Introduction/Background**
 - **LHP natural operating temperature**
 - **CC temperature and vapor front movement**
- **3 Types of Temperature Oscillation**
- **High Frequency Low Amplitude Temperature Oscillation**
 - **Governing equations**
 - **Factors affecting temperature oscillation**
- **Low Frequency High Amplitude Temperature Oscillation**
 - **Governing equations**
 - **Necessary conditions**
 - **Driving mechanism for temperature oscillation**
 - **Sequence of events**
 - **Factors affecting temperature oscillation**
- **Summary and Conclusions**



- The LHP operating temperature (CC temperature) is a function of
 - Evaporator power
 - Condenser sink temperature
 - Ambient temperature
- As the operating condition changes, the CC temperature will go through a transient period and eventually reach a new steady state temperature.



Governing Equations for Operation of an LHP without Attached Thermal Mass



$$Q_e = Q_{e,cc} + Q_{e,vap}$$

$$Q_{e,cc} = G_{e,cc} (T_e - T_{cc})$$

$$Q_{e,vap} = m\lambda$$

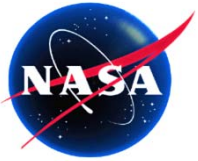
$$L_{vap} = Q_{e,vap} / [h\pi D (T_{cc} - T_{sink})]$$

$$T_{in} - T_{cond} = Q_{l,a} / (mC_p)$$

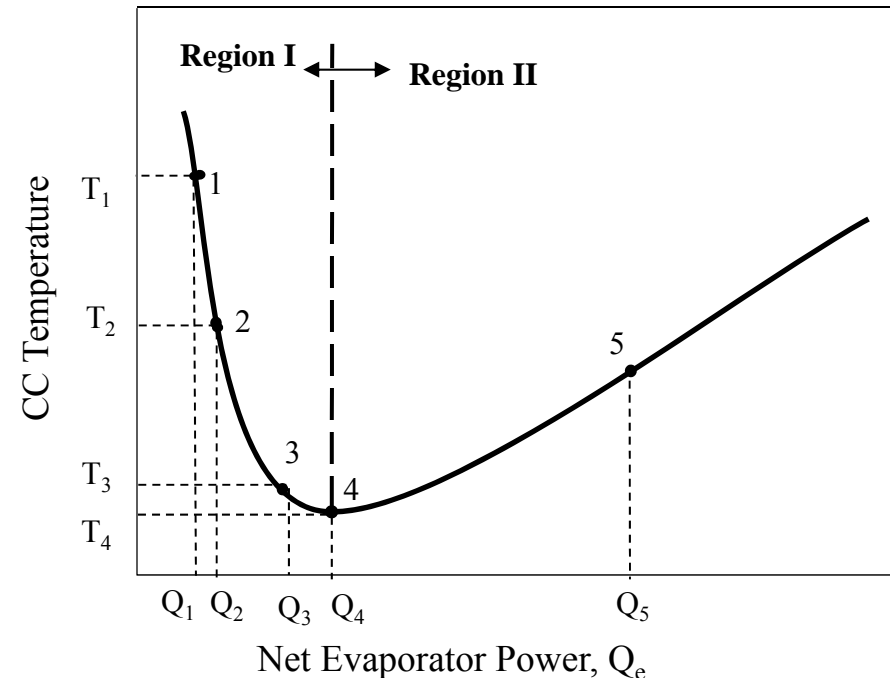
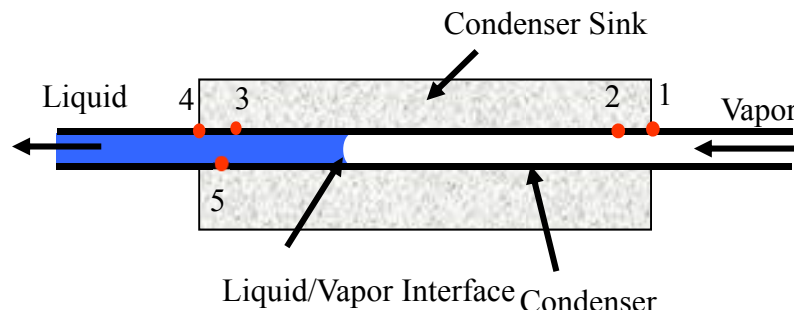
$$Q_{sub} = mC_p (T_{cc} - T_{in})$$

$$Q_{e,cc} = Q_{sub}$$

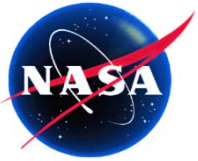
$$\Delta P = \lambda (T_e - T_{cc}) / (T_{cc} \Delta v)$$



LHP Operating Temperature without Attached Thermal Mass

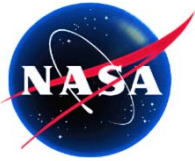


- The CC temperature of an LHP is well defined for a given evaporator power and sink temperature.
- Each point on the temperature curve also corresponds to a vapor front location inside the condenser.
- Under certain conditions, the CC temperature never reaches a true steady state, and displays oscillatory behaviors.



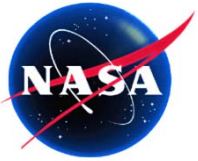
Three Types of LHP Temperature Oscillation

- **Ultra High Frequency Temperature Oscillation**
 - Periods less than 1 second; Amplitude is a tiny fraction of one Kelvin
 - Induced by vapor generation in evaporator and vapor condensation in condenser
 - No publications specifically dealing with this subject
- **High Frequency, Low Amplitude Temperature Oscillation**
 - Periods on the order of seconds to minutes; Amplitudes on the order of one Kelvin
 - Caused by vapor front movement near condenser inlet or exit
 - No large thermal mass attached to the evaporator
- **Low Frequency, High Amplitude Temperature Oscillation**
 - Periods on the order of hours
 - Amplitudes on the order of tens of Kelvin
 - Can be caused under various operating conditions



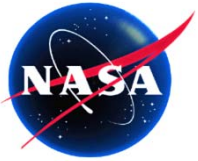
Papers Related to This Presentation on LHP Temperature Oscillations

- Ku, J., “High Frequency Low Amplitude Temperature Oscillations in Loop Heat Pipe Operation,” Paper No. 2003-01-2387, *33rd International Conference on Environmental Systems*, Vancouver, British Columbia, Canada, July 7-10, 2003.
- Ku, J., and J. Rodriguez, “Low Frequency High Amplitude Temperature Oscillations in Loop Heat Pipe Operation,” Paper No. 2003-01-2388, *33rd International Conference on Environmental Systems*, Vancouver, British Columbia, Canada, July 7-10, 2003.
- Hoang, T. and Baldauff, R., and Maxell, J., “Stability Theory for Loop Heat Pipe Design, Analysis and Operation,” Paper No. ICES-2015-14, *45th International Conference on Environmental Systems*, Bellevue, WA, July 12-16, 2015.
- Hoang, T. and Baldauff, R., and Tiu, C., “Verification of Loop Heat Pipe Stability Theory – Part I Low-Frequency/High-Amplitude Oscillations,” Paper No. ICES-2015-39, *45th International Conference on Environmental Systems*, Bellevue, WA, July 12-16, 2015.
- Hoang, T. and Baldauff, “Verification of Loop Heat Pipe Stability Theory – Part II High-Frequency/Low-Amplitude Oscillations,” Paper No. ICES-2015-XXX *45th International Conference on Environmental Systems*, Bellevue, WA, July 12-16, 2015.



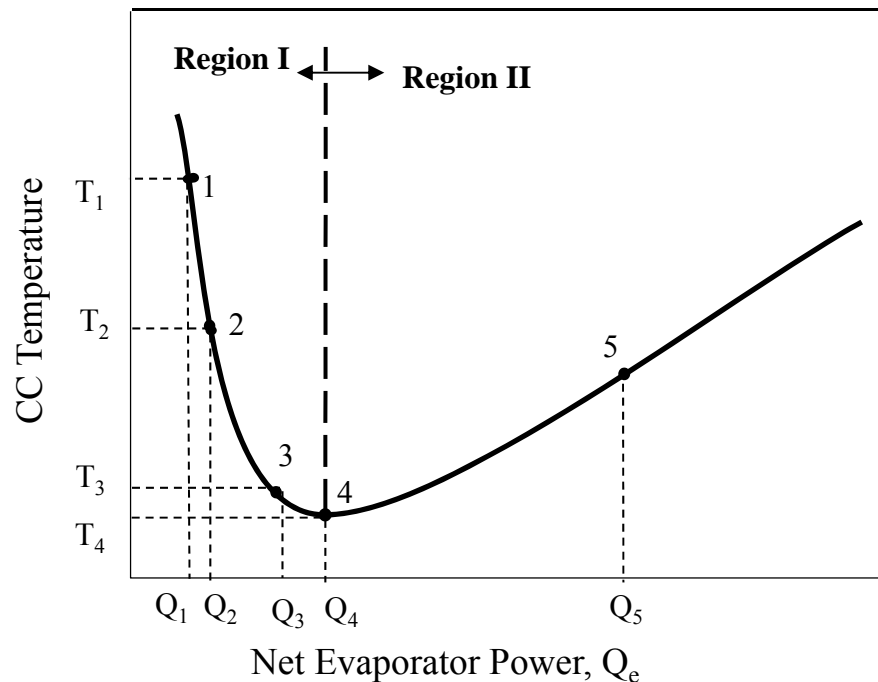
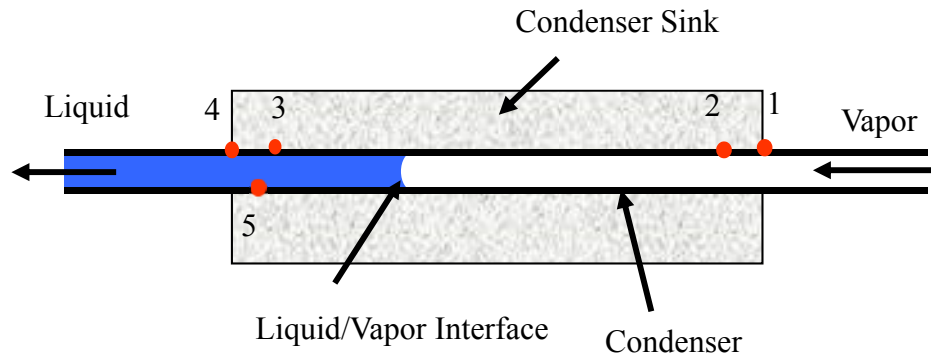
Scope of This Presentation

- **Refresh on LHP temperature oscillations**
- **Limit the discussion to LHPs with one evaporator and one condenser**
- **More detailed discussions on LHP temperature oscillations**
 - **Focus on the understanding of underlying physical processes**
 - **Interactions among LHP components and external conditions**
 - **The vapor front movement and the rise and fall of the CC temperature**
 - **The role of the attached large thermal mass in the modulation of the evaporator heat load**
 - **Sequence of events during temperature oscillations**
 - **Effect of thermal mass on high frequency low amplitude temperature oscillations**
 - **Analytical predictions of LHP temperature oscillations (paper by Hoang, et. al)**

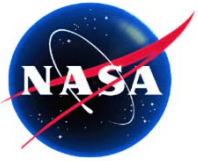


Vapor Front Stays Inside Condenser

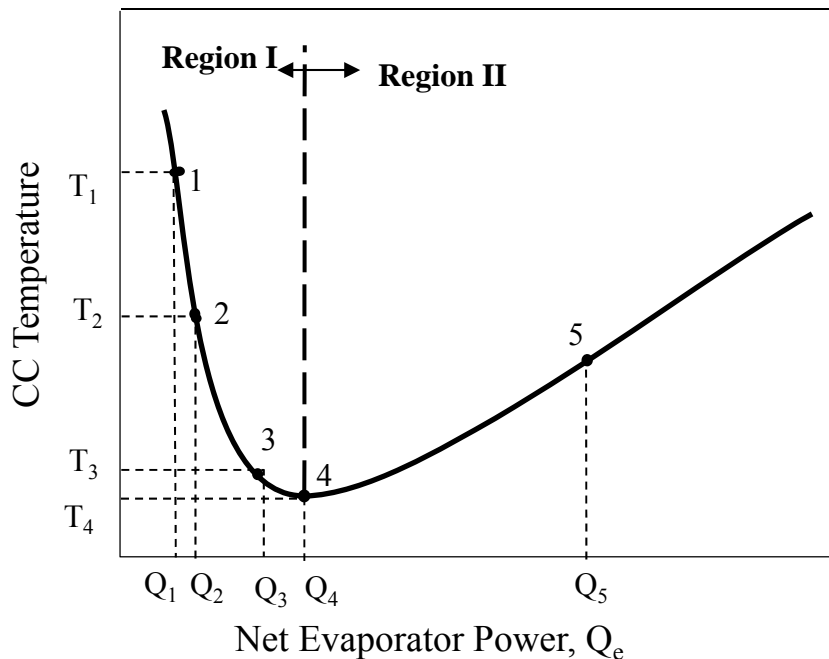
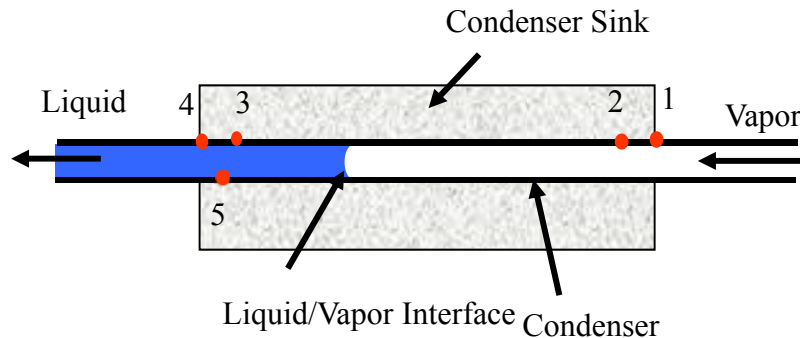
Stable LHP operating Temperature



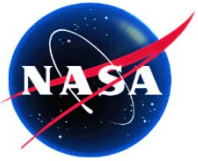
- A sharp vapor front is assumed.
- For a given heat load, a steady CC temperature can be obtained as long as the vapor front stays inside the condenser.
- For a given Q_e and T_{sink} , T_{cc} and L_{vap} are well-defined.
- When Q_e and/or T_{sink} changes, a new set of T_{cc} and L_{vap} can be found.
- An oscillating Q_e and vapor front movement will lead to an oscillating CC temperature.



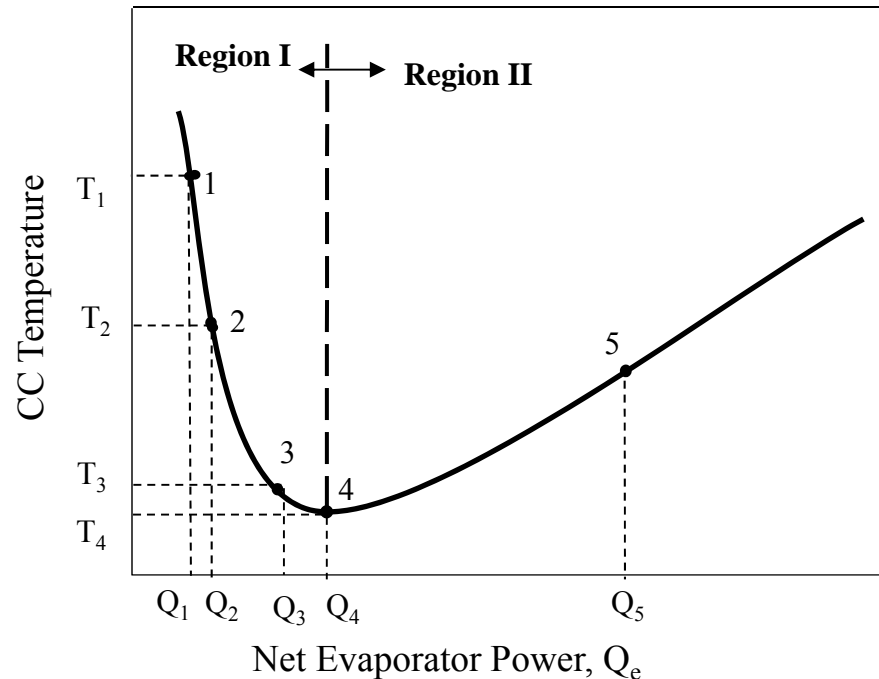
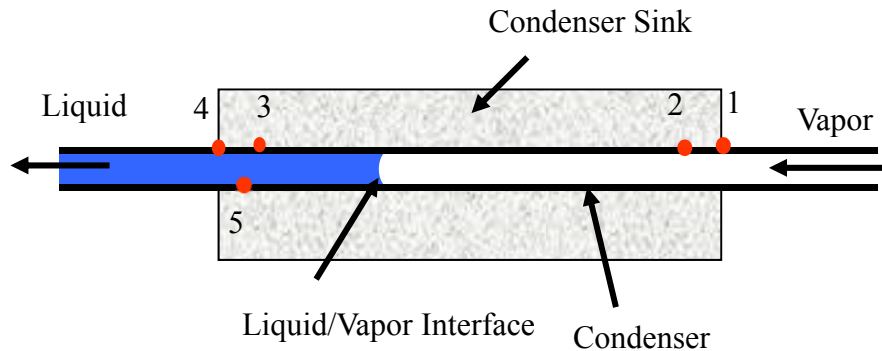
Vapor Front Near Condenser Exit



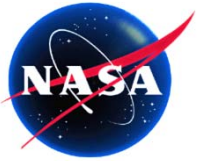
- When $Q_e \sim Q_4$, vapor front can pass the condenser exit. Warm liquid feeds into CC. T_{cc} continues to increase.
- Condenser is gaining higher and higher heat dissipating capability.
- When T_{cc} reaches a certain value, vapor front begins to recede back into condenser.
- Liquid subcooling increases as fluid flow exits the condenser.
- Cold liquid feeds into CC. T_{cc} continues to decrease.
- Condenser is losing its heat dissipating capability.
- When T_{cc} reaches a certain value, vapor front passes condenser exit again.
- The cycle repeats itself.
- T_{cc} and T_{cond} are nearly 180 degrees out of phase.



Vapor Front Near Condenser Inlet

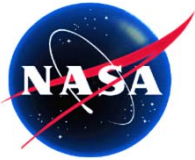


- At low power/low sink, vapor front moves near condenser inlet.
- T_{cc} increases due to decreasing subcooling. Vapor front moves into vapor line.
- Vapor line is not an efficient condenser. At some point, vapor line can no longer dissipate the heat load.
- Liquid slug is pushed into condenser rapidly. T_{cc} decreases. The rapid vapor front movement into condenser overshoots.
- Vapor front recedes afterwards. T_{cc} increases. Vapor front recedes further into vapor line.
- The cycle repeats itself.
- Without thermal mass, vapor front does not move far from location 1.

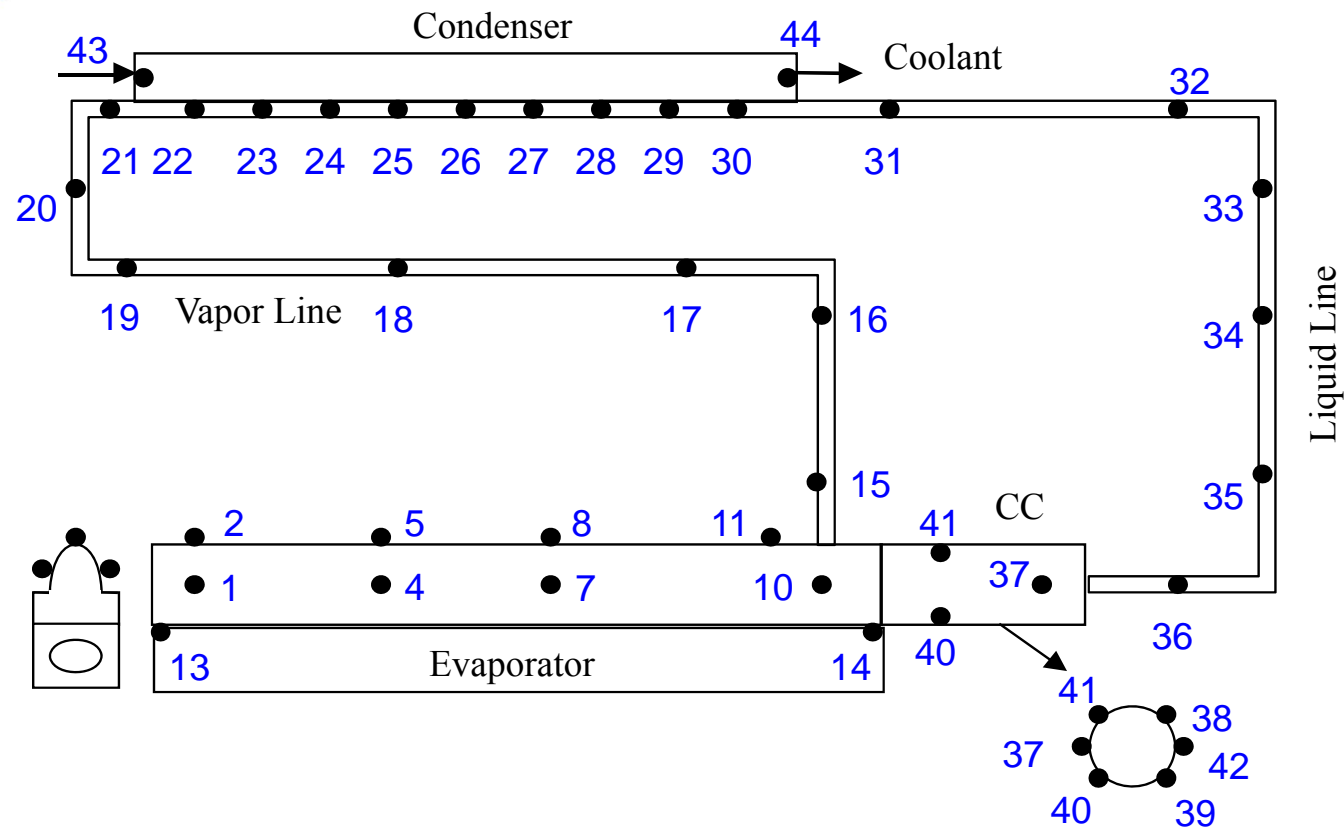


Factors Affecting High Frequency Low Amplitude Temperature Oscillations

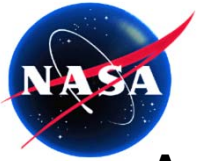
- **The high frequency low amplitude temperature oscillation will disappear when the vapor front moves away from the condenser inlet or exit. Conversely, it will appear when the vapor front moves near the condenser inlet or exit.**
- **Factors that affect the vapor front location**
 - **Evaporator power**
 - **Condenser sink temperature**
 - **Ambient temperature**
 - **Body forces**
 - **Active control of CC temperature**
- **Some experimental results from testing of two LHPs are presented. Both LHPs were tested extensively for various studies of LHP operation.**



LHP1 with Thermocouple Locations

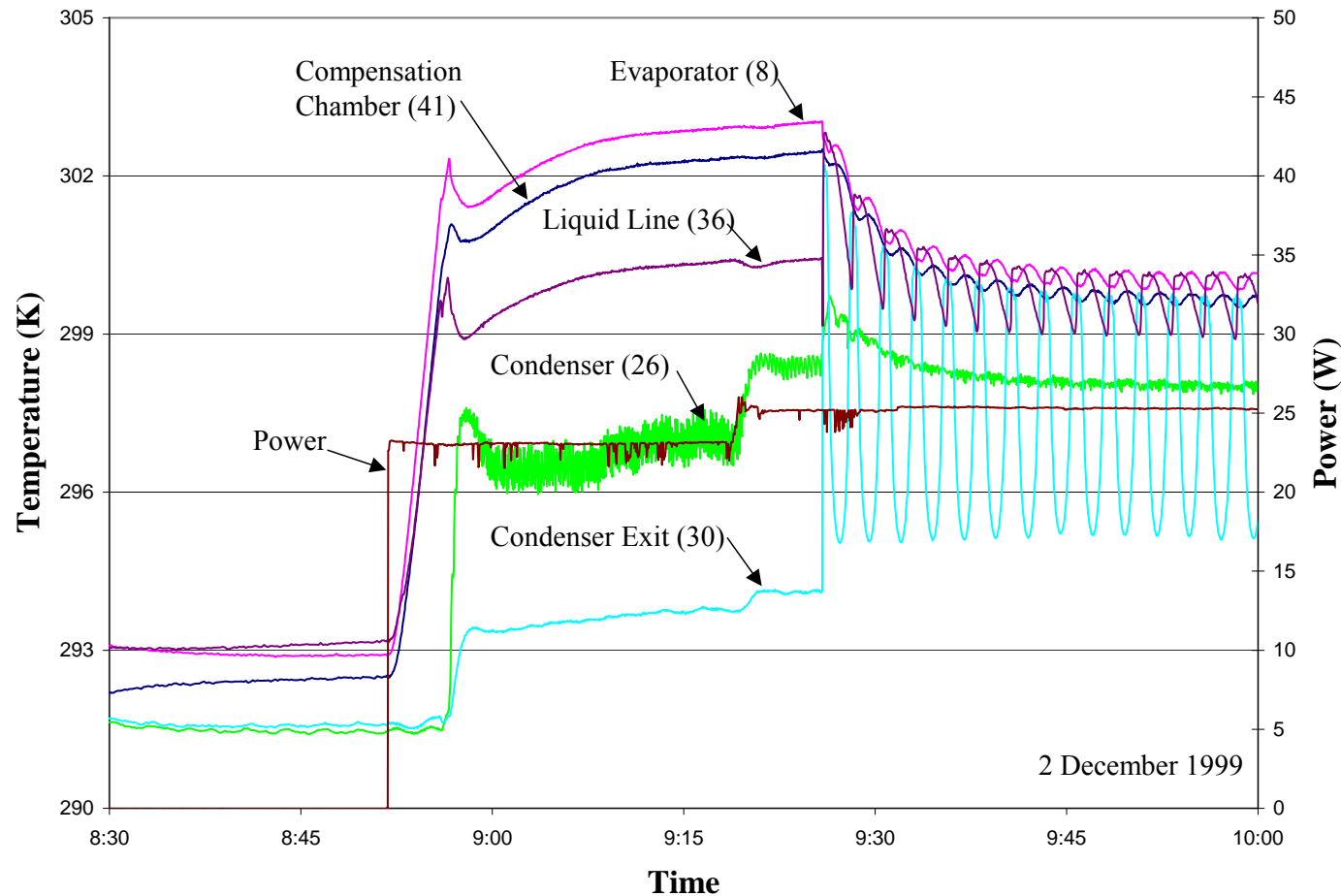


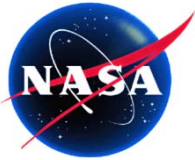
- **Evaporator:** 12.7 mm diameter and 120 mm length
- **Vapor line:** 2.8 mm I.D. and 160 mm length
- **Liquid line:** 2.8 mm I.D. and 130 mm length
- **Condenser:** 2.8 mm I.D. and 100 mm length



LHP1 Operating Temperature vs Heat Load

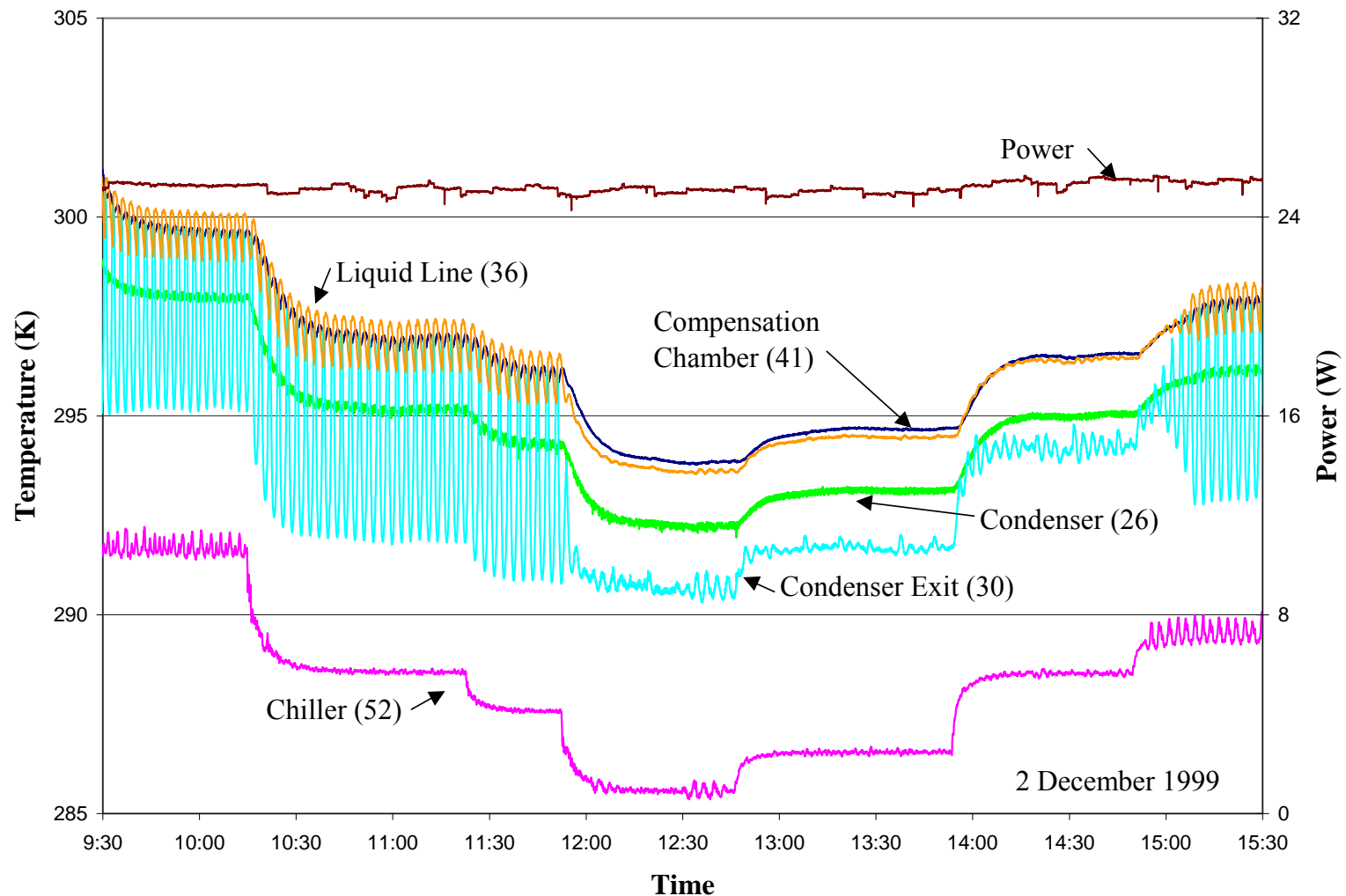
- An increase of power from 23W to 25W caused the vapor front to move near condenser exit, inducing temperature oscillations.
- Vapor front moved around the condenser exit during oscillation.

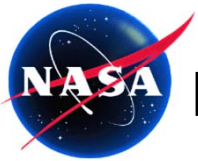




LHP 1 Operating Temperature vs Sink Temperature

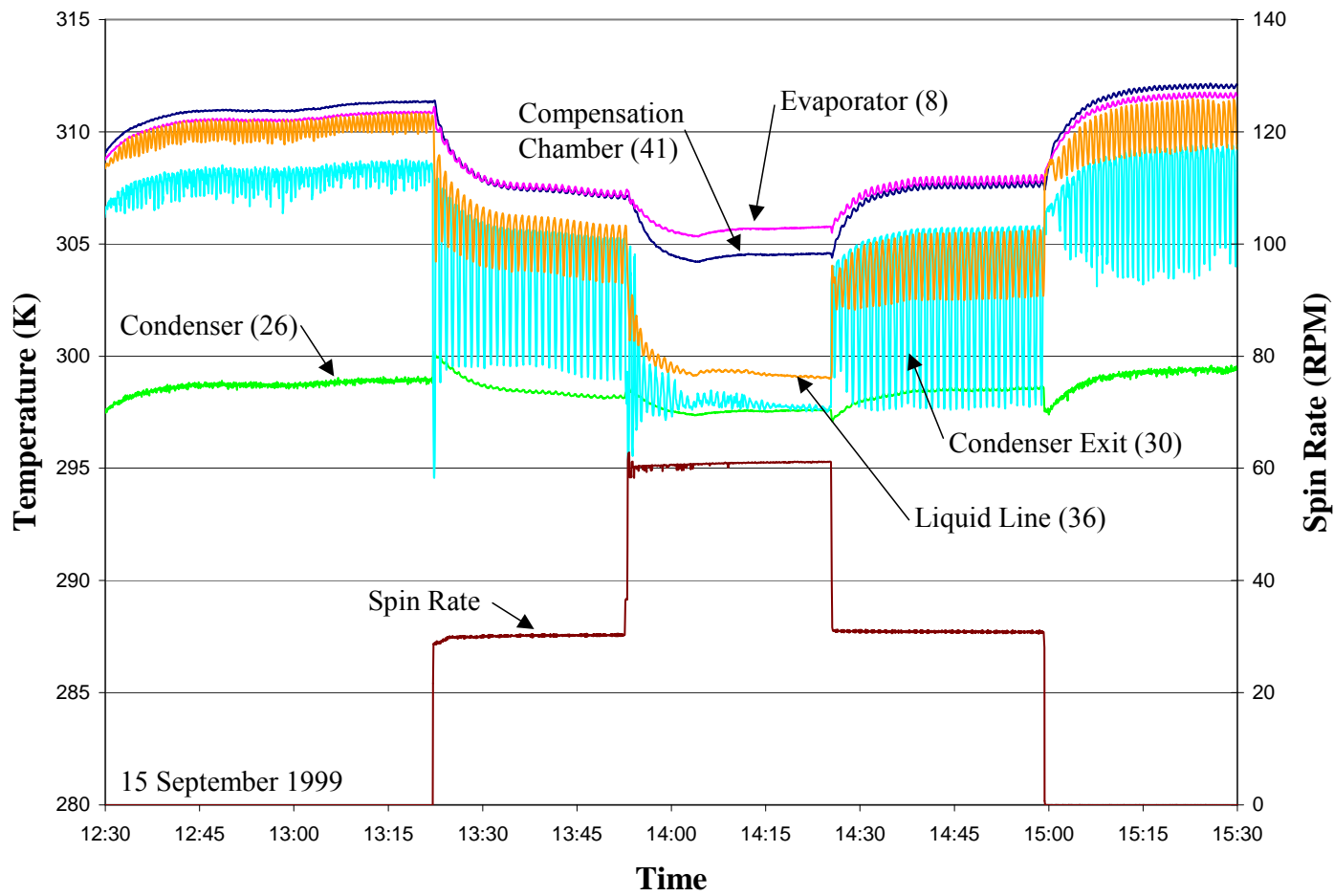
- When the sink temperature reduced to 287K or lower, the vapor front moved inside the condenser away from the exit, eliminating temperature oscillations.

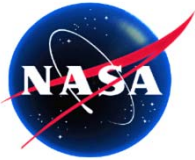




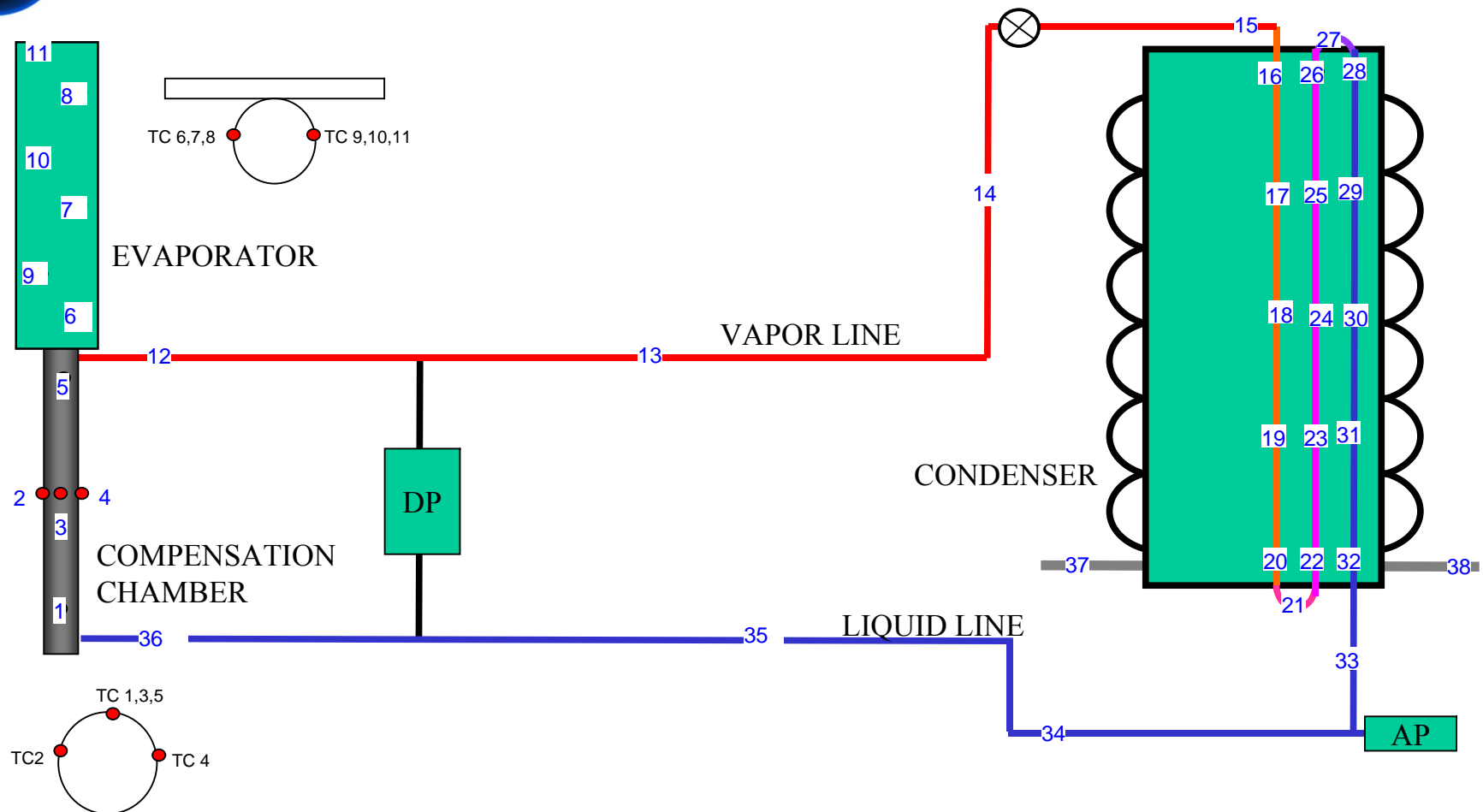
LHP 1 Operating Temperature vs Spin Rate (100W/273K)

- The centrifugal force changed the fluid distribution inside the LHP and the vapor front location in the condenser, and hence affected temperature oscillation.

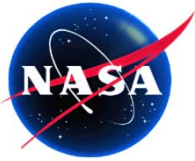




LHP2 with Thermocouple Locations

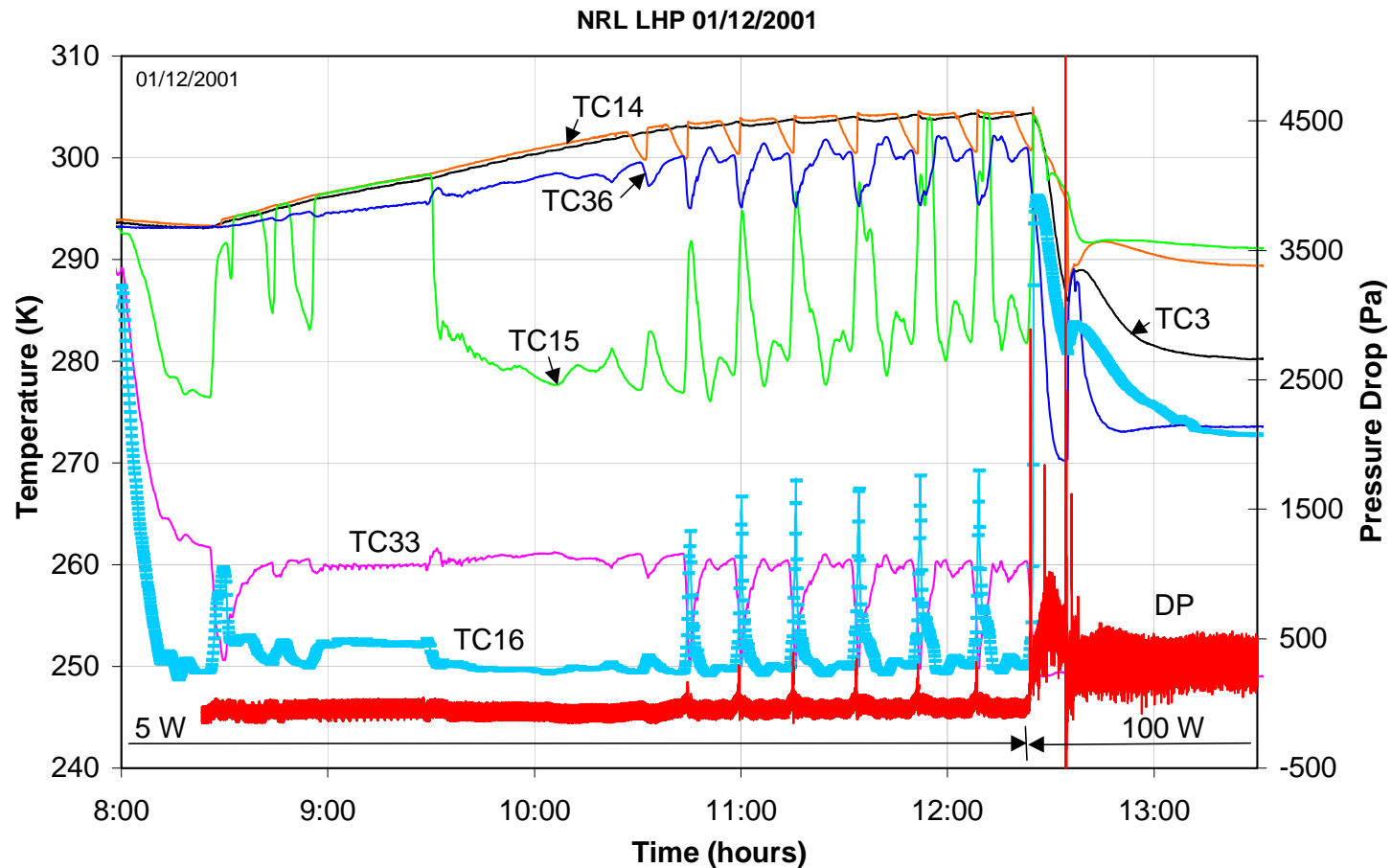


- **Evaporator:** 25.4 mm diameter and 300 mm length
- **Vapor line:** 3.34 mm I.D. and 1500 mm length
- **Liquid line:** 1.75 mm I.D. and 1500 mm length
- **Condenser:** 3.86 mm I.D. and 2000 mm length

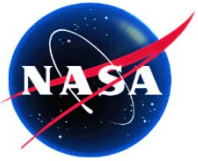


LHP2 Temperature Oscillations (100g/5W/248K)

- Back and forth movement of the vapor front near the condenser inlet caused temperature oscillation.

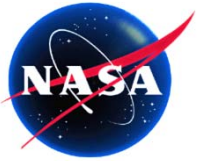


TC3 - CC, TC7 - Evap., TC14/15- Vapor Line, TC16- Cond, TC33 - Liq Line, TC36 - CC Inlet



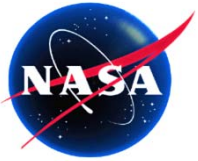
High Frequency Low Amplitude Temperature Oscillations – Summary of the Theory

- **High frequency low amplitude temperature oscillation can happen under the following two conditions when no thermal mass is attached to the evaporator:**
 - **The vapor front moves back and forth near the condenser exit. The LHP operates under a fixed conductance mode.**
 - **The vapor front moves back and forth near the condenser inlet. The LHP operates under a variable conductance mode.**
- **The movement of the vapor front in the condenser causes a change in the flow rate and/or temperature of the liquid flow in the liquid line. This in turn changes the subcooling of the liquid returning to the CC, leading to the CC temperature change.**
 - **Neither liquid line or vapor line is an efficient condenser.**
- **The interaction of the CC temperature and the liquid subcooling causes the temperature oscillation in the loop.**
- **Without a large thermal mass attached to the evaporator, the CC and the loop can adopt to the change quickly, leading to a high frequency low amplitude temperature oscillations.**



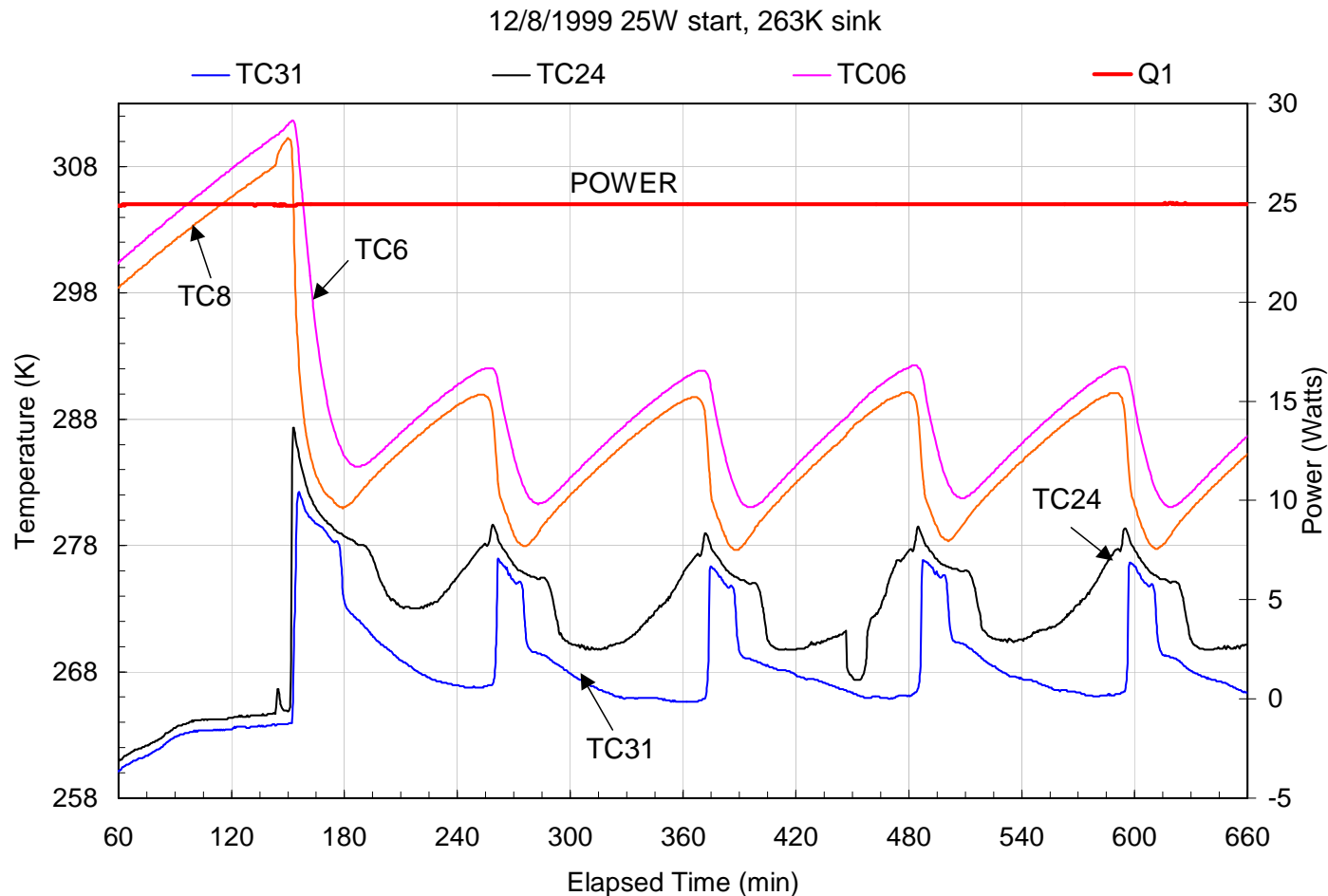
Low Frequency High Amplitude Temperature Oscillations Observed in LHPs

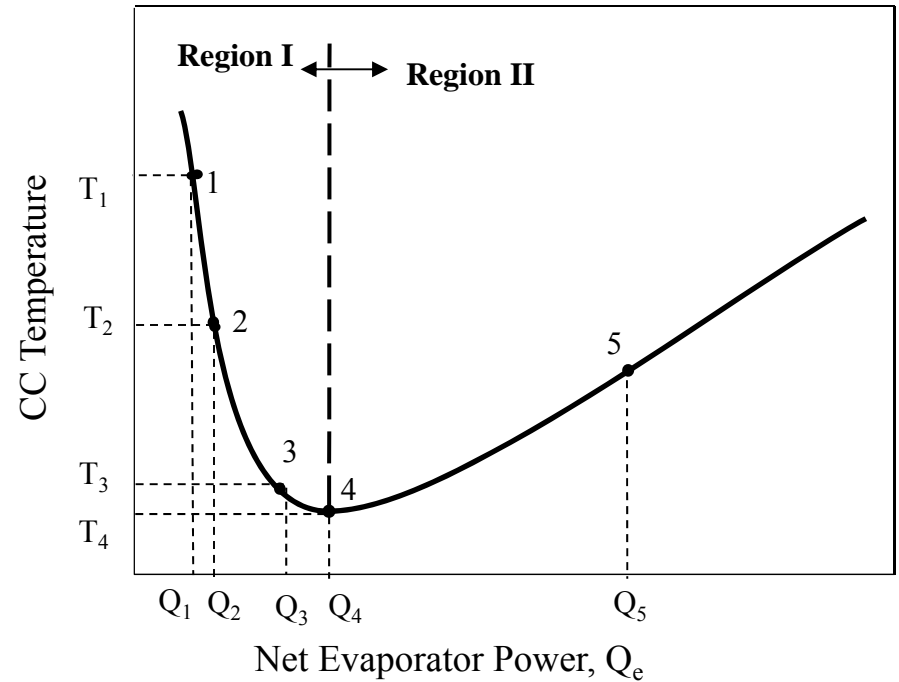
- **Constant Applied Power and Oscillating Sink Temperature**
 - Observed in flight or simulated thermal vacuum tests.
 - Results are expected.
- **LHP with a Single Evaporator and Two Parallel Condensers/Radiators**
 - One sink is colder than saturation temperature, the other is warmer.
 - The flow regulator with warm sink dries out periodically.
 - Oscillations can be eliminated by placing the two flow regulators side by side.
 - **Not covered in this presentation**
- **Periodic partial Druout of the Secondary Wick During Power Transient for LHP with a Large Thermal Mass Attached to Evaporator**
 - **Not cover in this presentation**
- **LHP with a Large Thermal Mass Attached to Evaporator**
 - Constant heat load to thermal mass
 - Constant sink temperature
 - **Focus of this presentation**



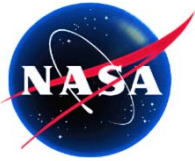
Example of Low Frequency High Amplitude Temperature Oscillations Observed in TES LHP EDU

- Amplitudes of temperature oscillation: CC (TC8) ~ 12K, TM (TC6) ~ 10K
- Period of temperature oscillation: ~ 2 hours.

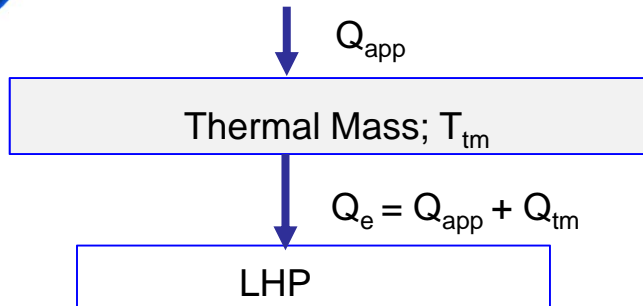




- The LHP operation is a function of the net load to the evaporator, Q_e , not the heat load to the thermal mass, Q_{app} .
- The large thermal mass can modulate the constant heat load Q_{app} into an oscillating Q_e received by the evaporator under certain conditions.
- An oscillating Q_e causes temperature oscillations.



Heat Load Modulation by Thermal Mass

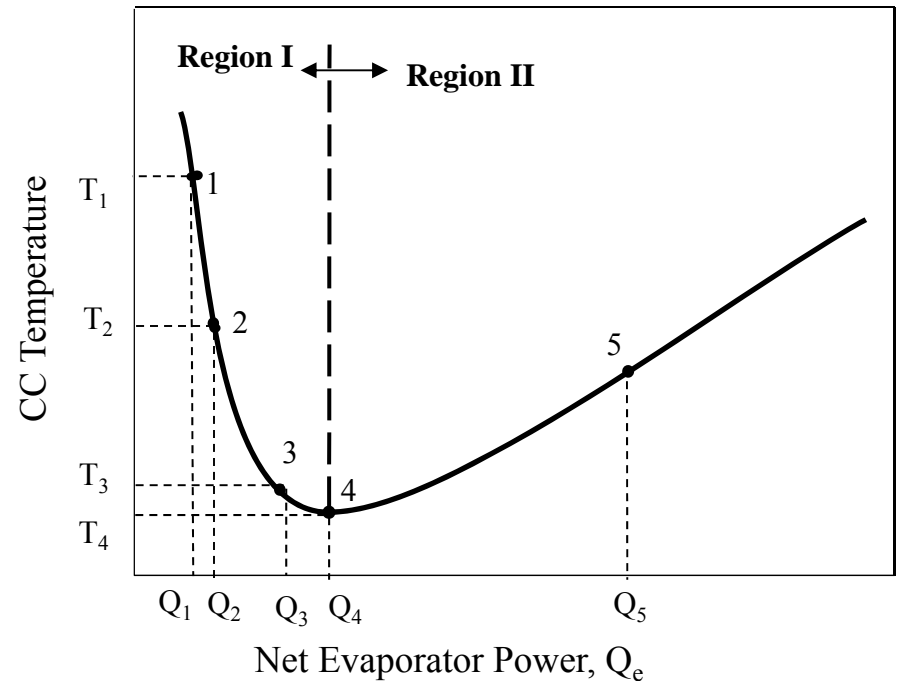


$$Q_{tm} = -M_{tm} C_{p,tm} \frac{dT_{tm}}{dt}$$

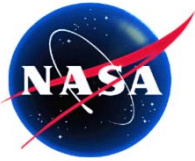
$$Q_e = Q_{app} + Q_{tm}$$

$$Q_e = G_{e,tm} (T_{tm} - T_e)$$

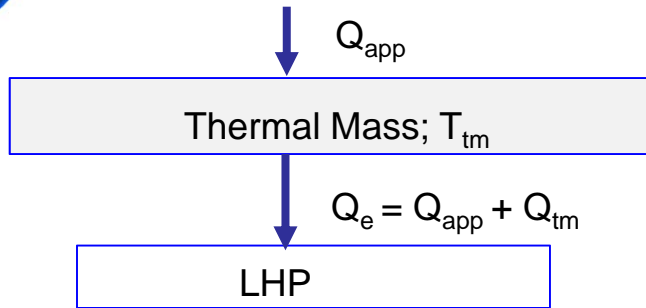
$$L_{vap} = Q_e / [h\pi D (T_{cc} - T_{sink})]$$



- **TM modulates Q_e by absorbing or releasing heat.**
- **$Q_{tm} < 0$, $Q_e < Q_{app}$ when TM is absorbing heat and T_{tm} is increasing.**
- **$Q_{tm} > 0$, $Q_e > Q_{app}$ when TM is releasing heat and T_{tm} is decreasing.**
- **Under certain conditions, Q_e can oscillate between a maximum and a minimum, leading to low frequency high amplitude temperature oscillations.**



Heat Load Modulation by Thermal Mass

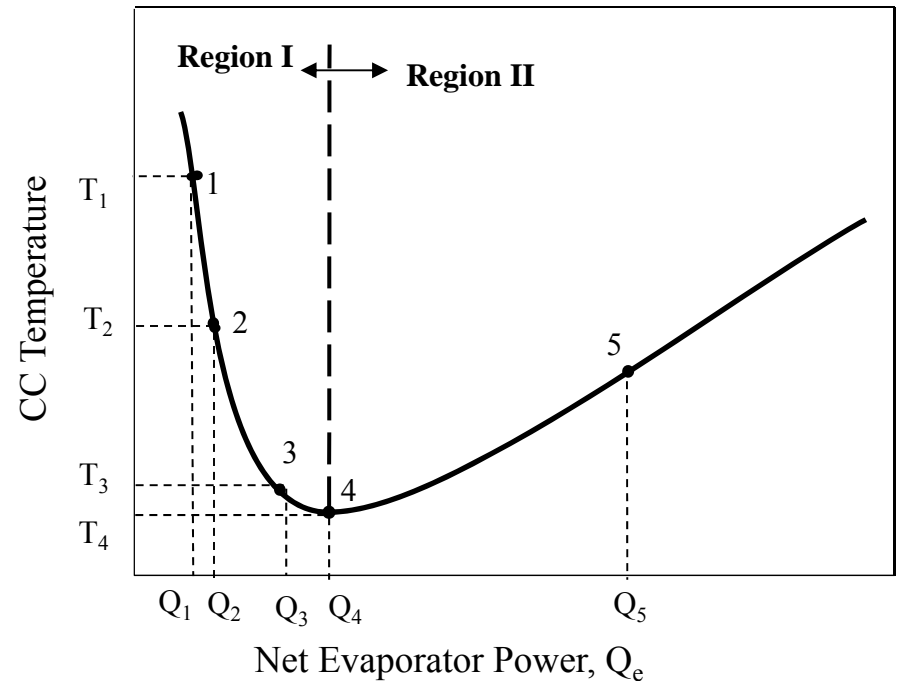


$$Q_{tm} = -M_{tm} C_{p,tm} \frac{dT_{tm}}{dt}$$

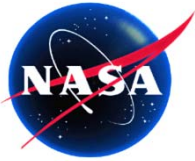
$$Q_e = Q_{app} + Q_{tm}$$

$$Q_e = G_{e,tm} (T_{tm} - T_e)$$

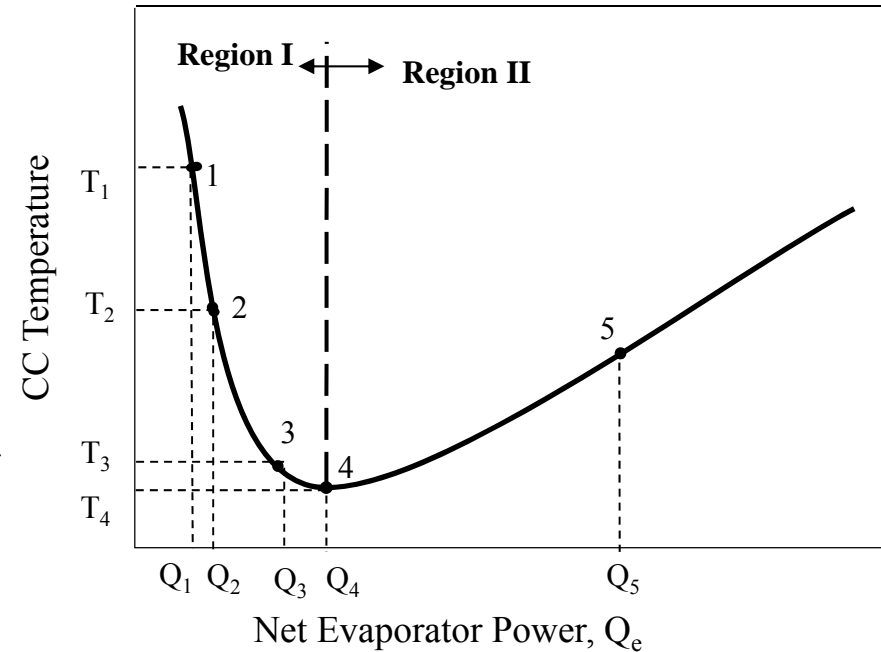
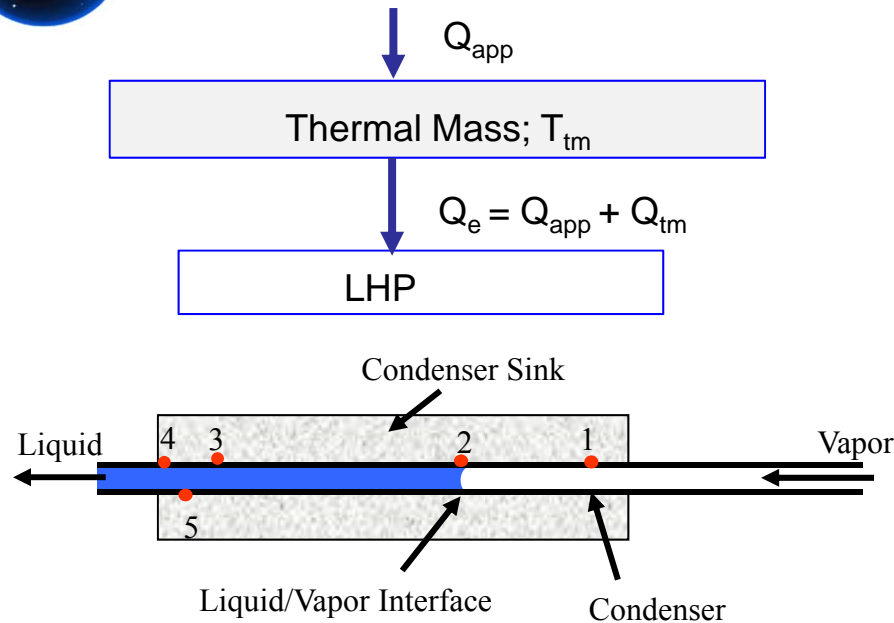
$$L_{vap} = Q_e / [h\pi D (T_{cc} - T_{sink})]$$



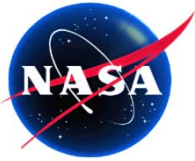
- **Low frequency high amplitude temperature oscillations can only happen in Region I under the variable conductance mode. It cannot happen in Region II under the fixed conductance mode.**
- **In region I, T_{cc} decreases with an increasing heat load Q_e , which amplifies the effect of heat load modulation by thermal mass.**
- **In region II, T_{cc} increases with an increasing heat load Q_e , which counterbalances the effect of heat load modulation by thermal mass.**



Heat Load Modulation by Thermal Mass

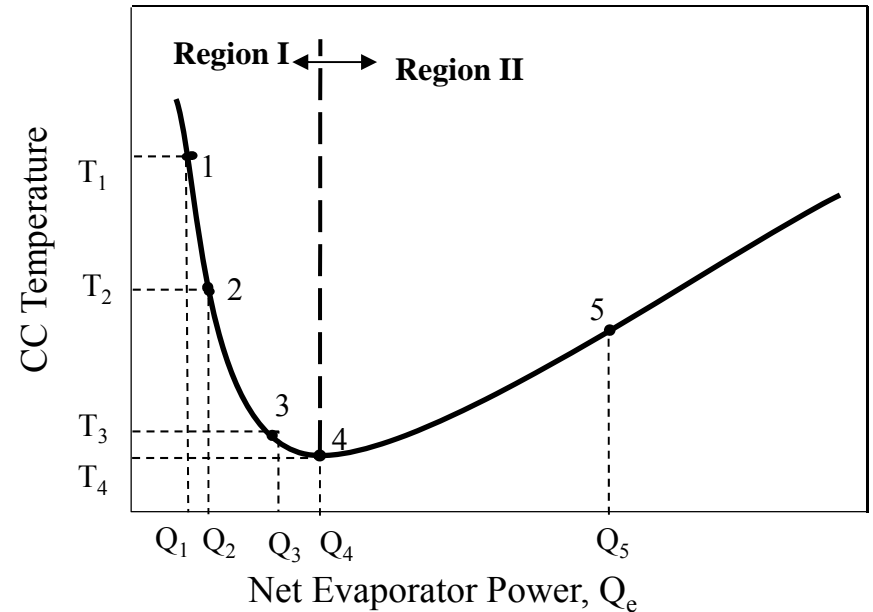
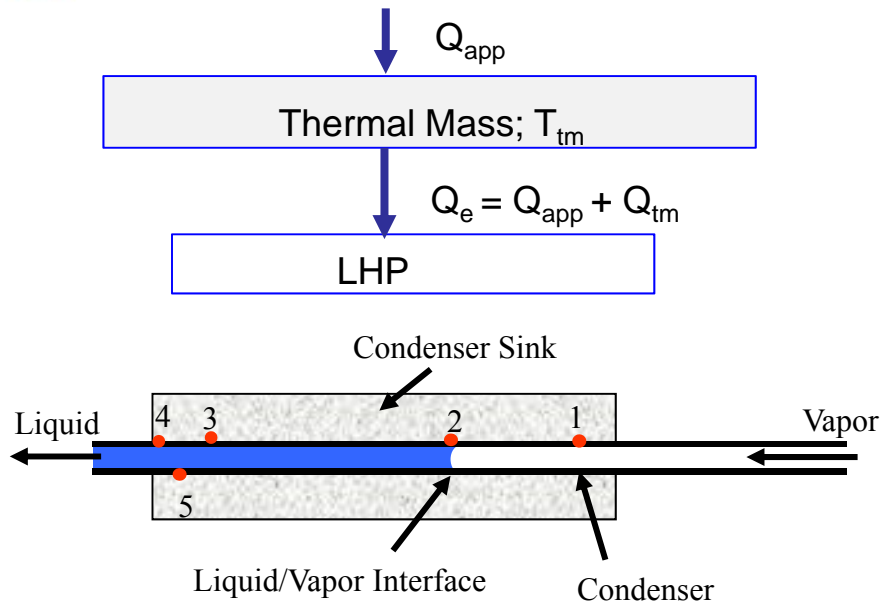


- There is a one-to-one correspondence among Q_e , T_{cc} and L_{vap} .
- Without TM, $Q_e = Q_{app} \equiv Q_2$, $T_{cc} = T_2$ and the vapor front stays at location 2.
- When a large TM is attached to the LHP evaporator, the TM can modulate the constant heat load Q_2 into an oscillating Q_e that varies between Q_1 and Q_3 . As a result, T_{cc} varies between T_1 and T_3 , and the vapor front moves between location 1 and location 3.
- When the vapor front is between location 1 and location 2, TM absorbs heat and $Q_e < Q_{app}$. When the vapor front is between location 2 and location 3, TM releases heat and $Q_e > Q_{app}$.

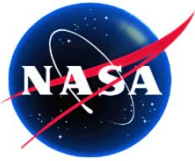


Heat Load Modulation by Thermal Mass

Vapor Front Moves from Location 2 to Location 3

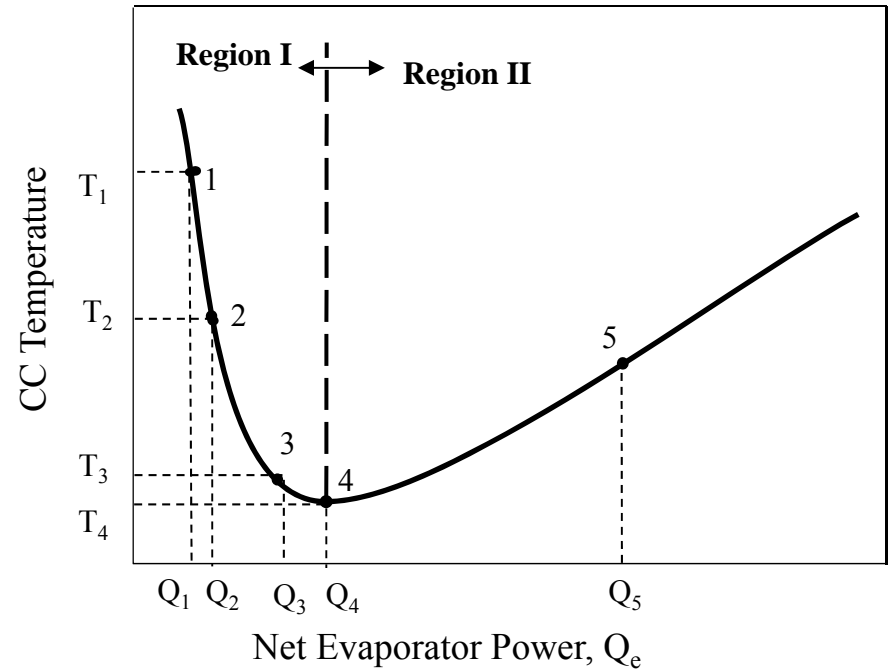
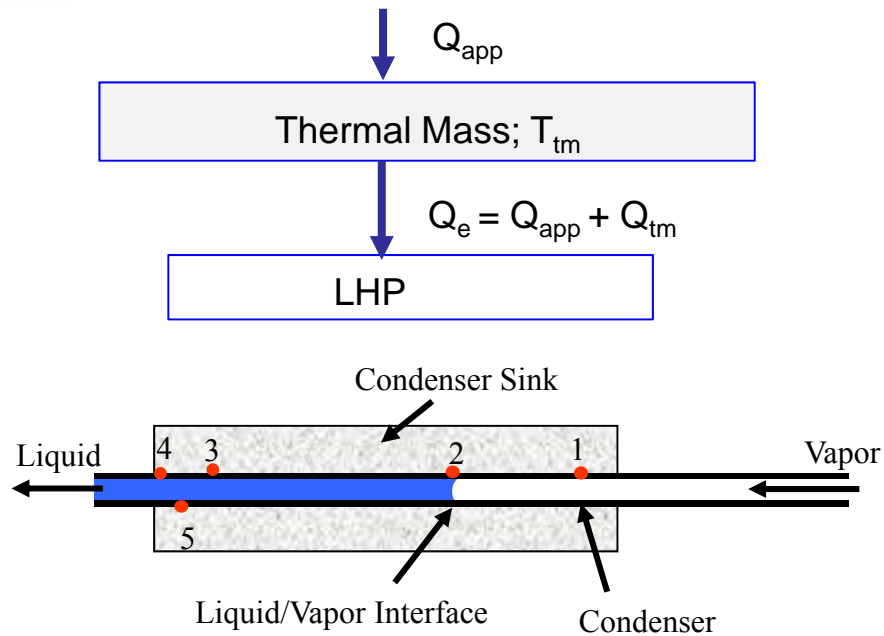


- Without TM, $Q_e = Q_{app} \equiv Q_2$, $T_{cc} = T_2$ and the vapor front stays at location 2.
- If a TM with a temperature $T_{tm} > T_e$ is attached to evaporator, additional heat Q_{tm} will flow into the LHP. L_{vap} will increase and T_{cc} will decrease.
- The decrease of T_{cc} leads to an increase in Q_{tm} , Q_e , and L_{vap} .
- T_{tm} will decrease at a slower rate than T_{cc} , leading to a further increase of Q_{tm} , Q_e , and L_{vap} . This trend continues until L_{vap} reaches its maximum and T_{cc} reaches its minimum at location 3.
- At location 3, $(T_{tm} - T_{cc})$ reaches a maximum and TM cannot release any higher Q_{tm} to support a further increase of L_{vap} and further decrease of T_{cc} .

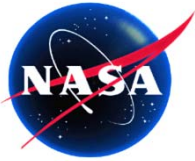


Heat Load Modulation by Thermal Mass

Vapor Front Moves from Location 3 to Location 2

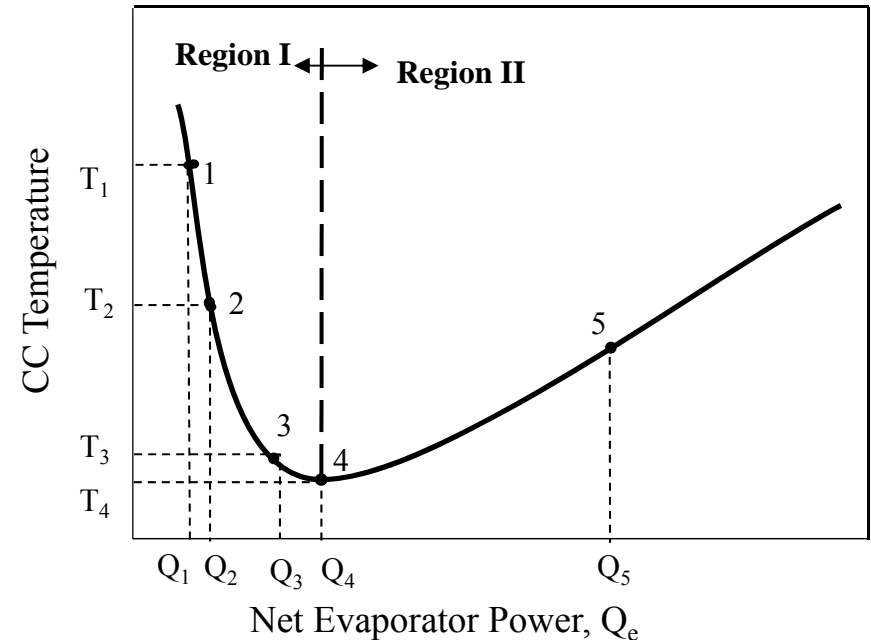
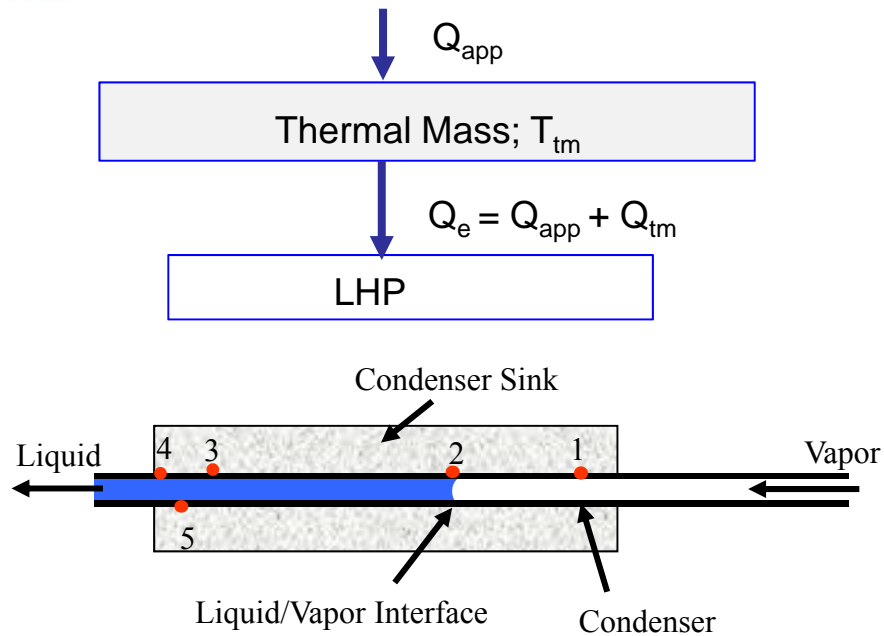


- T_{cc} begins to increase, which leads to a decrease in Q_{tm} , Q_e , and L_{vap} .
- Q_{tm} and Q_e are decreasing, and the TM is releasing heat at a slower and slower rate. The trend continues until the vapor front reaches location 2. Note: $Q_{tm} > 0$, and $Q_e > Q_{app}$ during this period.
- At location 2, TM reaches its minimum temperature and release no heat. $Q_{tm} = 0$, and $Q_e = Q_{app}$. $T_{cc} = T_2$, the LHP natural operating temperature.

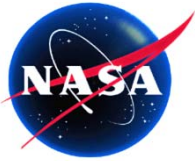


Heat Load Modulation by Thermal Mass

Vapor Front Moves from Location 2 to Location 1

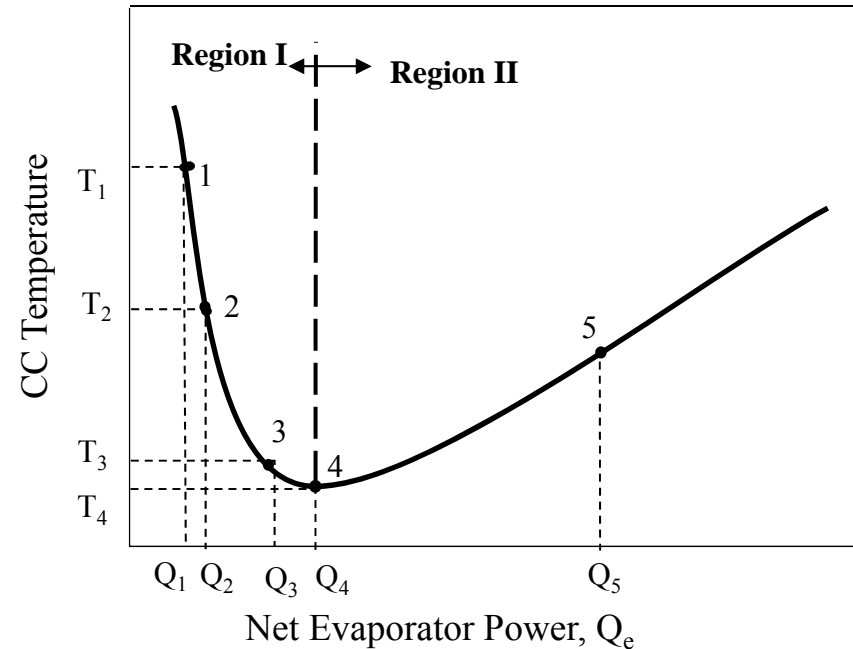
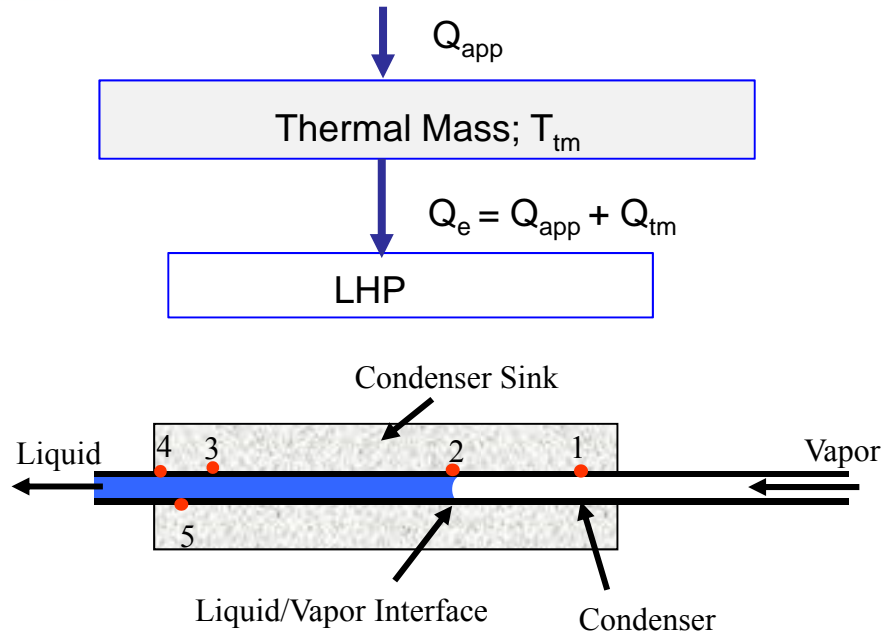


- T_{tm} begins to increase from its minimum. $Q_{tm} < 0$, $Q_e < Q_{app}$.
- $Q_{app} = Q_e - Q_{tm}$. Q_{app} has to support the increase of T_{tm} and sustain the LHP operation simultaneously. Both T_{cc} and T_{tm} rise very slowly.
- Still, T_{cc} rises at a faster rate (decreasing liquid subcooling) than that of T_{tm} .
- $(T_{tm} - T_{cc})$ continues to decrease. As a result, Q_e and L_{vap} continue to decrease. This trend continues until the vapor front reaches location 1.
- At location 1, T_{cc} is at its maximum based on energy balance of heat leak and liquid subcooling. $(T_{tm} - T_{cc})$ and Q_e are at their minima. An increase of T_{tm} will lead to an increase of Q_e . Note: $Q_{tm} < 0$, and $Q_e < Q_{app}$ during this period.

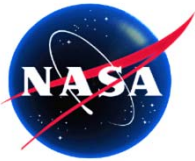


Heat Load Modulation by Thermal Mass

Vapor Front Moves from Location 1 to Location 2

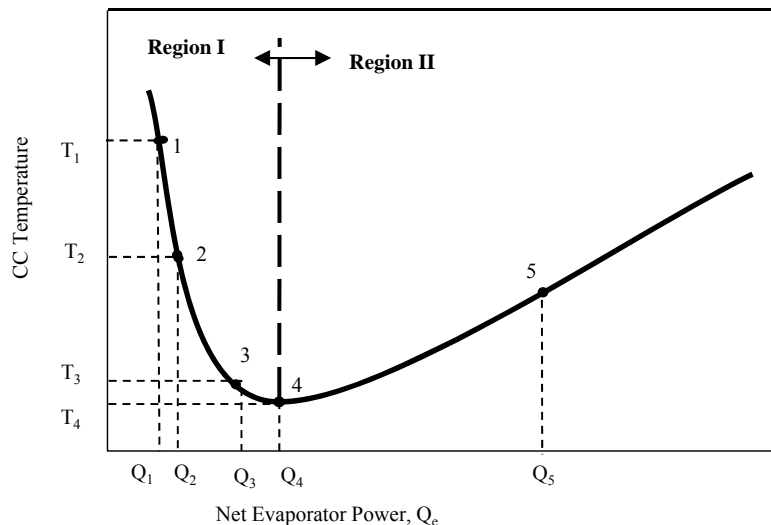
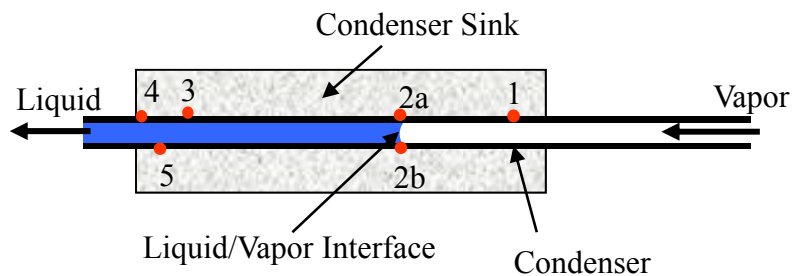
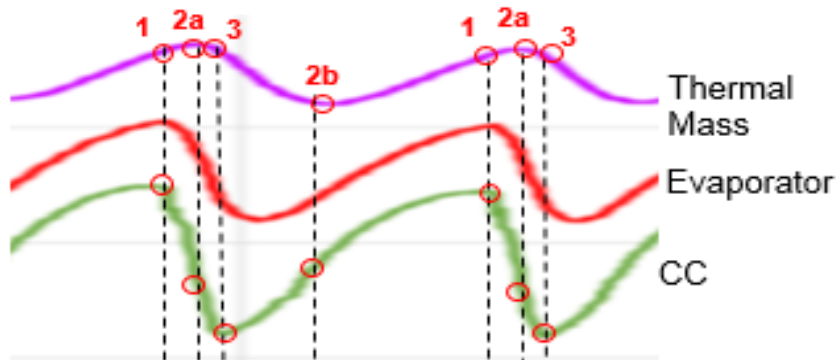


- $(T_{tm} - T_{cc})$ begin to increase from its minimum. Q_e begin to increase. T_{tm} increases at a slower rate (gets less heat from Q_{app}). T_{cc} begin to decrease.
- Q_{tm} , Q_e , T_{cc} , and L_{vap} increase at faster and faster rates while T_{tm} increases at a slower and slower rate until vapor front reaches location 2.
- At location 2, $Q_{tm} = 0$, TM reaches its maximum temperature and absorbs no heat. $Q_e = Q_{app}$. TM has its maximum sensible heat in storage. $T_{cc} = T_2$, the LHP natural operating temperature.
- The entire temperature oscillation cycle repeats subsequently.

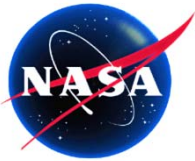


Heat Load Modulation by Thermal Mass

Summary of Sequence of Events

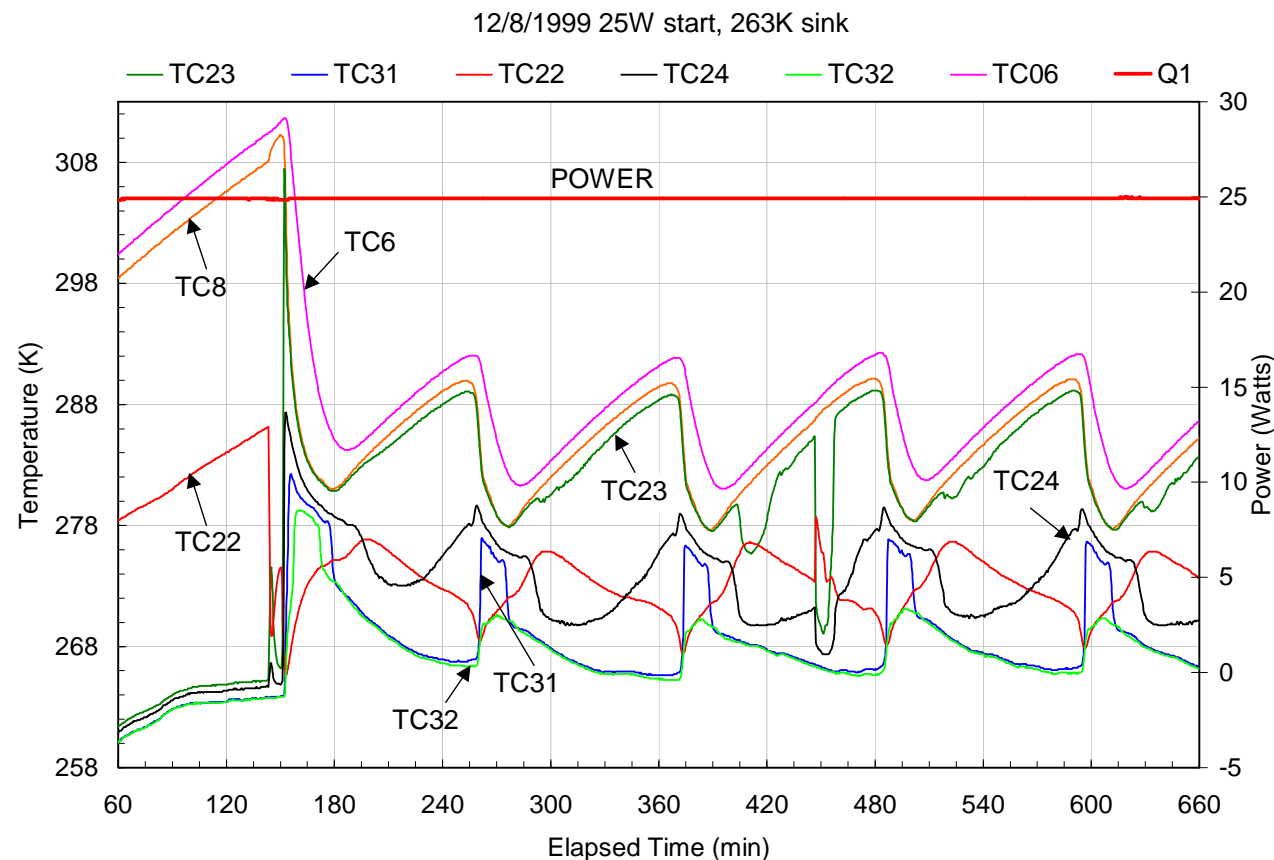


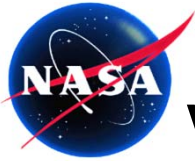
Vapor Front	Major Events
Point 1	T_{cc} at maximum; L_{vap} at minimum; Q_{tm} and Q_e at minima; TM absorbs energy at fastest rate; inflection point for T_{tm}
Point 1 to Point 2a	T_{cc} decreases at an increasing rate; Q_{tm} and Q_e increase at increasing rates; TM absorbs heat at a decreasing rate; $Q_e < Q_{app}$
Point 2a	T_{tm} at maximum; $Q_{tm} = 0$; $Q_e = Q_{app}$; inflection point for T_{cc}
Point 2a to Point 3	T_{cc} decreases at a decreasing rate; T_{tm} decreases at an increasing rate; Q_{tm} and Q_e increase at increasing rates; $Q_e > Q_{app}$
Point 3	T_{cc} at minimum; L_{vap} at maximum; Q_{tm} and Q_e at maxima, TM releases heat at fastest rate; inflection point for T_{tm} ; $Q_e > Q_{app}$
Point 3 to Point 2b	T_{cc} increases at an increasing rate; Q_{tm} and Q_e decrease at decreasing rates; T_{tm} decreases at a decreasing rate; $Q_e > Q_{app}$
Point 2b	T_{tm} at minimum; $Q_{tm} = 0$; $Q_e = Q_{app}$; inflection point for T_{cc}
Point 2b to Point 1	T_{cc} increases at a decreasing rate; Q_e decreases at a decreasing rate; TM absorbs heat at an increasing rate; $Q_e < Q_{app}$



Temperature Oscillation in TES LHP EDU (25W/263K)

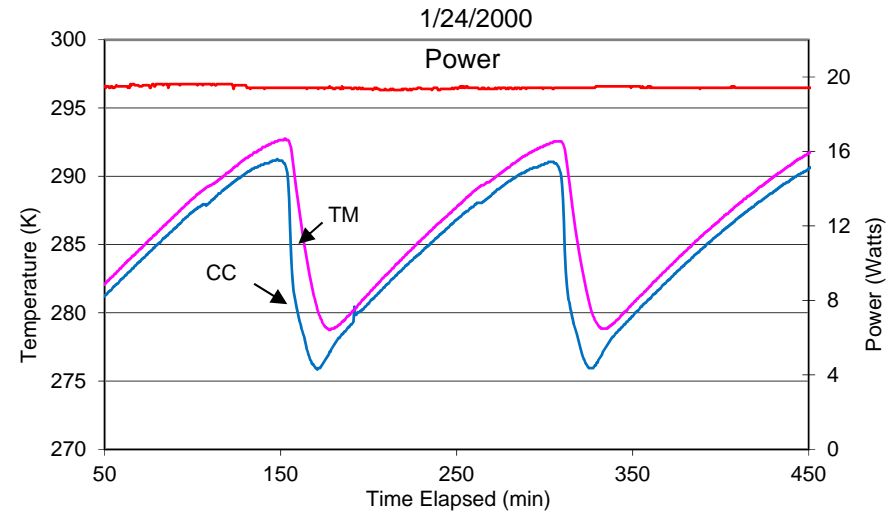
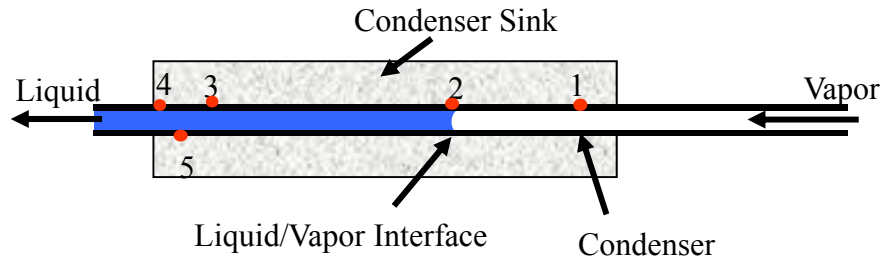
- The above discussions of vapor front movement can start from any vapor front location.
- The results below show that the LHP started with a superheat, underwent an initial transient, then began temperature oscillation that could last indefinitely.



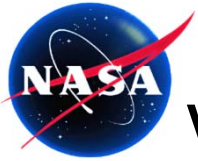


Heat Load Modulation by Thermal Mass

Vapor Front Movement during Temperature Oscillation Cycles

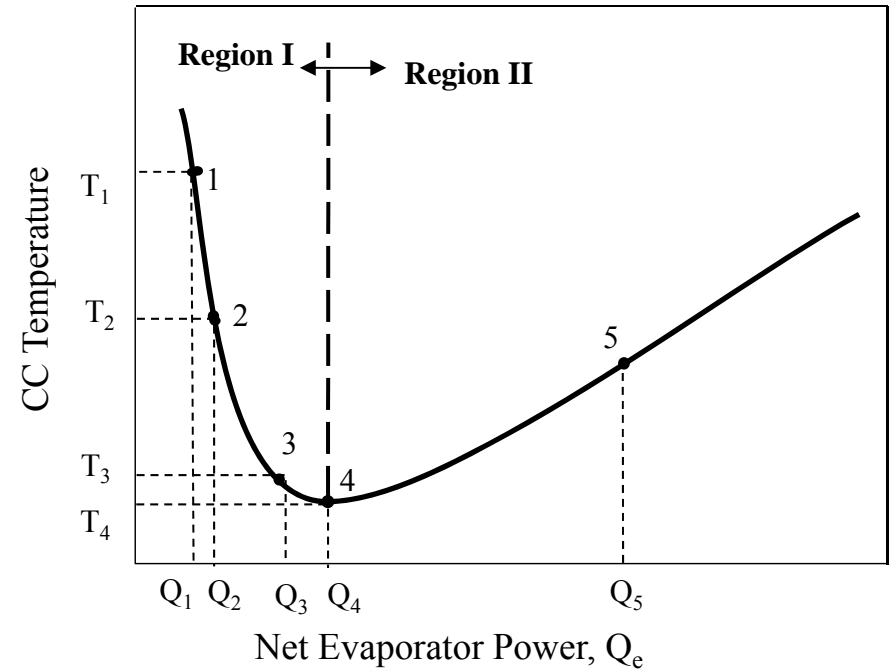
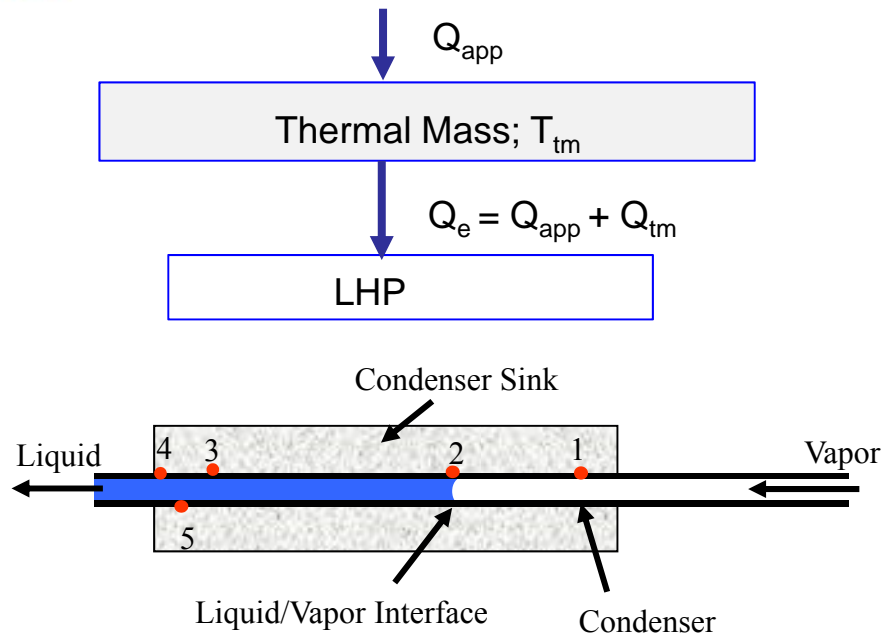


- The movement of vapor front from location 1 to location 3 (T_{cc} decreasing) is much faster than that from location 3 to location 1 (T_{cc} increasing), i.e. the temperature curve is asymmetric.
- When T_{cc} is decreasing, the TM can accelerate its heat release. When T_{cc} is rising, T_{tm} must also rise above T_{cc} so that it can provide the heat needed to sustain the LHP operation. The large thermal mass and the limited Q_{app} that is available makes T_{tm} to rise slowly.
- The curve becomes more asymmetric with a lower power and/or a lower sink temperature.

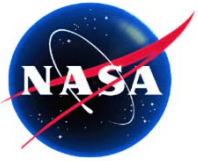


Heat Load Modulation by Thermal Mass

Vapor Front Movement during Temperature Oscillation Cycles

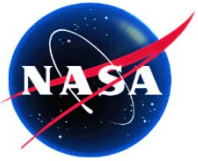


- The range of the vapor front movement can be correlated to the amplitude of the temperature oscillation.
- The amplitude and period of temperature oscillation increase with:
 - Decreasing sink temperature
 - Decreasing heat load
 - Increasing thermal mass
- Vapor front can never pass much beyond the condenser exit.



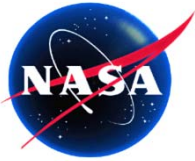
Low Frequency High Amplitude Temperature Oscillation – Summary of the Theory

- **With a constant sink, an oscillating heat input to the evaporator will lead to temperature oscillations in the LHP.**
- **Under certain conditions, the large thermal mass attached to the evaporator can modulate a constant applied heat load into an oscillating heat input to the evaporator, causing the loop temperature to oscillate.**
 - **The thermal mass absorbs energy when its temperature is rising and releases energy when its temperature is falling.**
 - **The net heat load to the evaporator oscillates between a maximum that is higher than the applied power, and a minimum that is lower than the applied power.**
- **The temperature oscillation, once started, can continue indefinitely until the operating condition changes.**

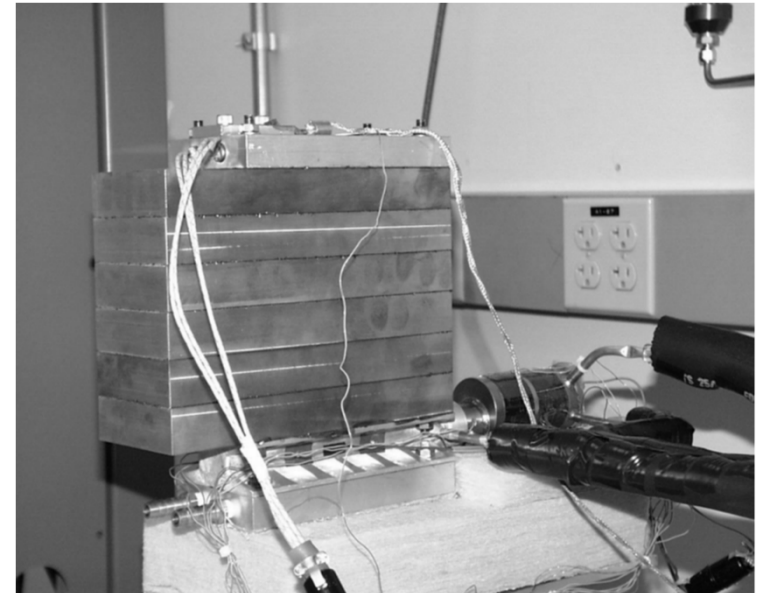
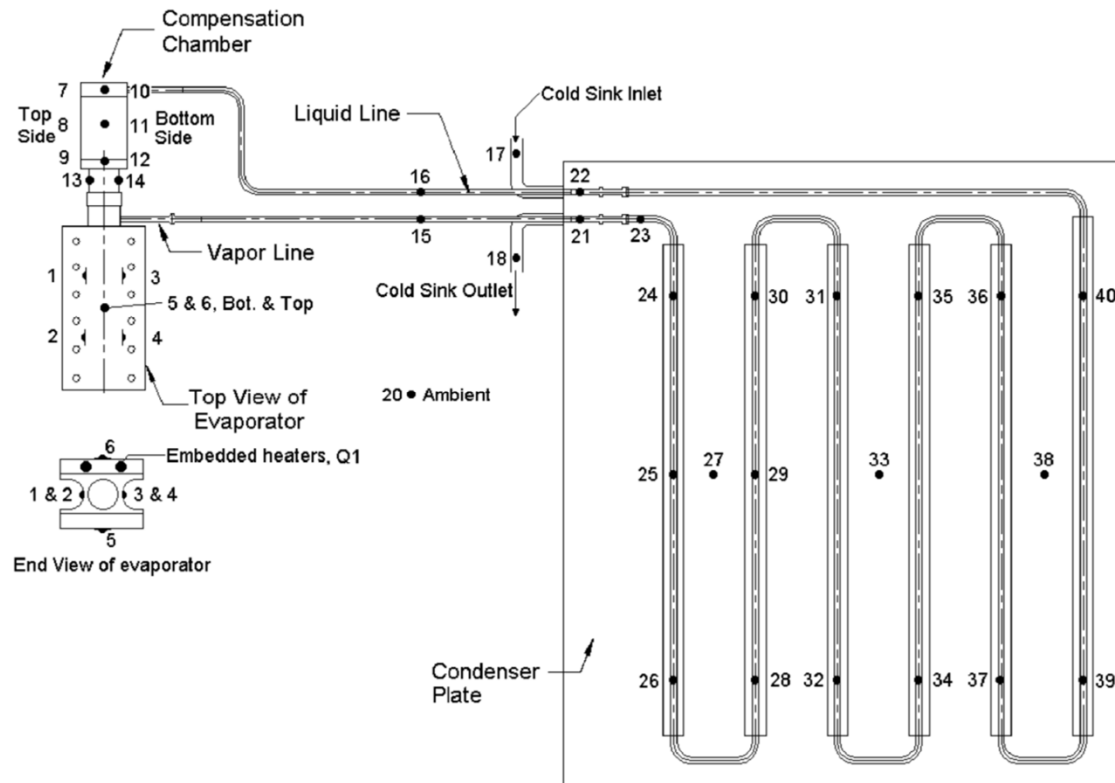


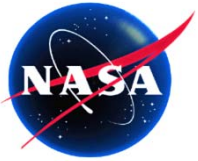
Low Frequency High Amplitude Temperature Oscillations – Necessary Conditions

- **In order to sustain a low frequency high amplitude temperature oscillation, all of the following three conditions must prevail:**
 - **A large thermal mass is attached to the evaporator.**
 - **A small power is applied to the thermal mass.**
 - **The condenser has a cold sink (colder than the surrounding temperature)**
- **The terms “large thermal mass,” “small power,” and “cold sink” are all relative.**
 - **No absolute values can be assigned.**
 - **Analytical tool exists (Hoang & Baldauff).**



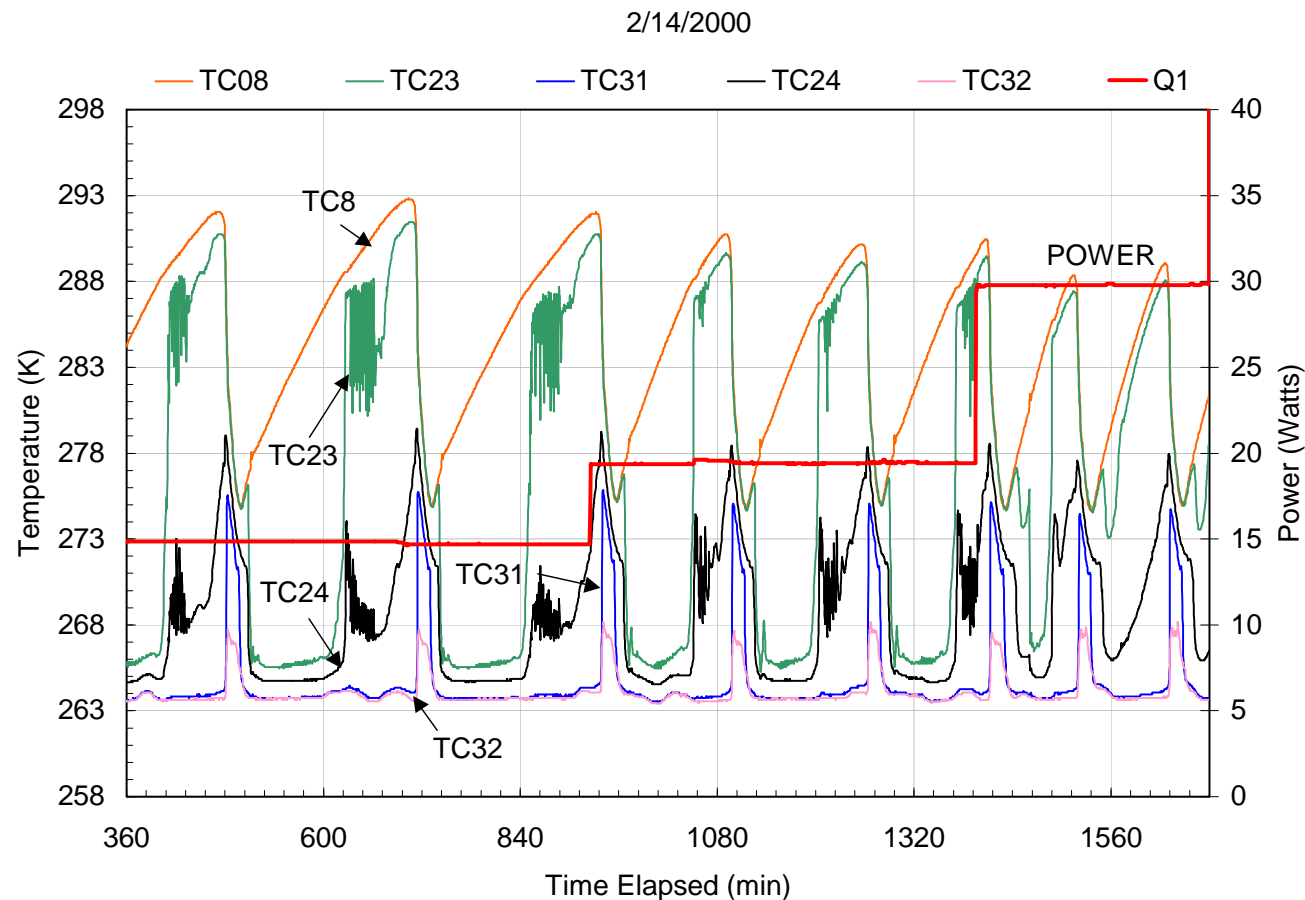
Temperature Oscillation in TES LHP EDU

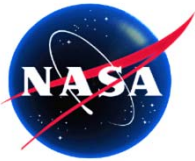




Temperature Oscillation in TES LHP EDU (263K, 15W/ 20W/ 30W)

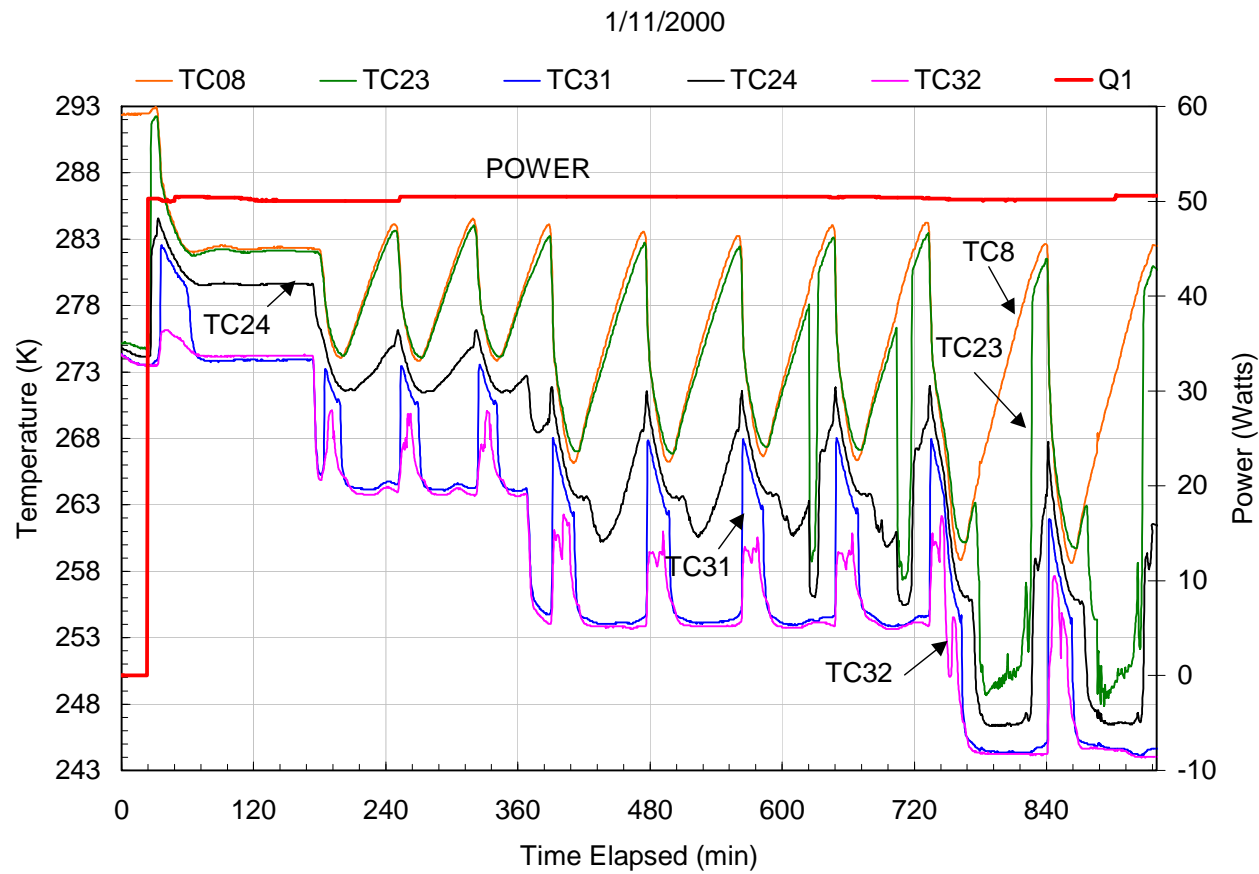
- Lower power leads to a large amplitude and a longer period of temperature oscillation.
- The periods for temperature rise and fall become more asymmetric with a decreasing power.

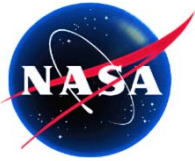




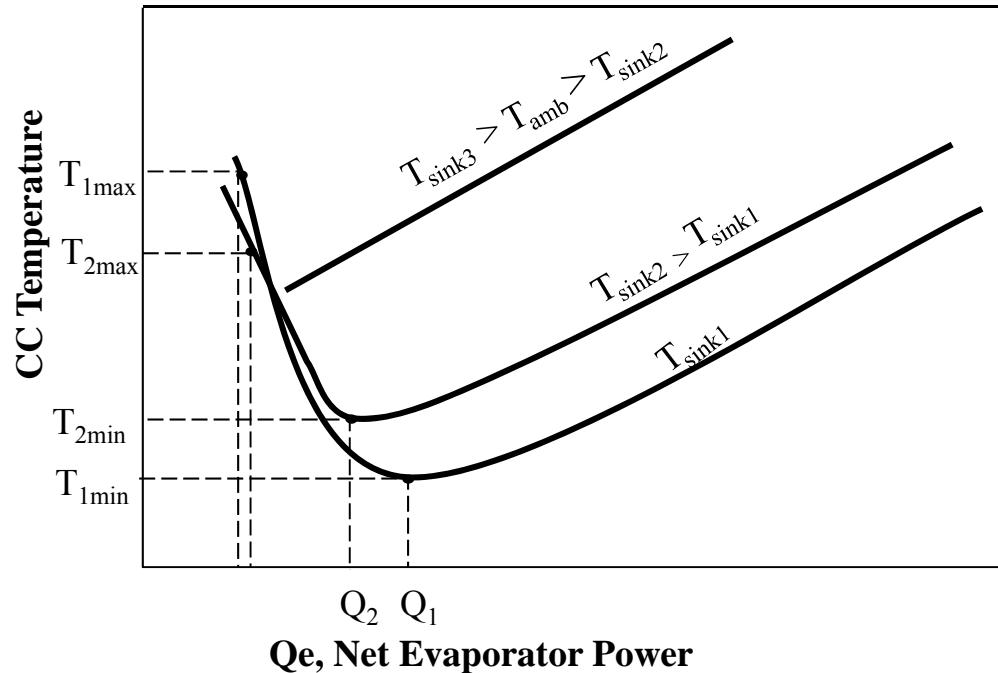
Temperature Oscillation in TES LHP EDU (50W, 273K/ 263K/ 253K/ 243K)

- Lower sink temperature leads to a large amplitude and a longer period of temperature oscillation.
- The periods for temperature rise and fall become more asymmetric with a decreasing sink temperature.

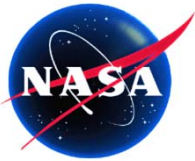




Effect of Sink Temperature on CC Temperature

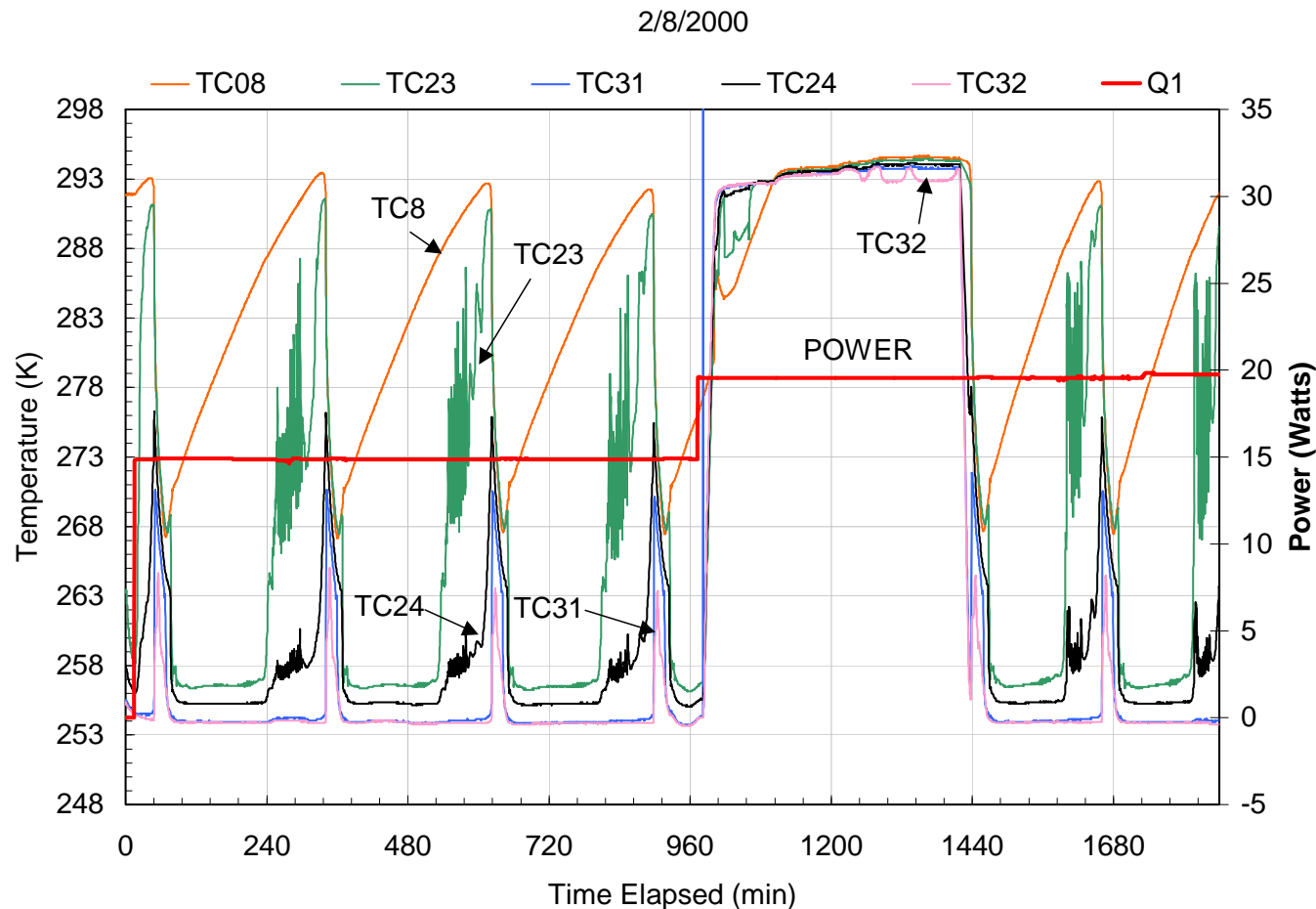


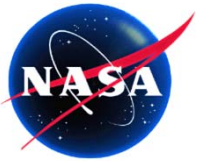
- Each curve represents the natural operating temperature at the given sink temperature.
- Lower sink temperature allows TM to give out more sensible heat when its temperature is decreasing ($T_{1min} < T_{2min}$) and to store more sensible heat when its temperature is rising ($T_{1max} > T_{2max}$). This translates to a larger range for vapor front movement and a higher amplitude and a longer period for temperature oscillation.
- No temperature oscillation will occur when the sink temperature is higher than ambient temperature (no heat load modulation by TM)



Temperature Oscillation in TES LHP EDU (15W/253K, 20W/293K, 20W/253K)

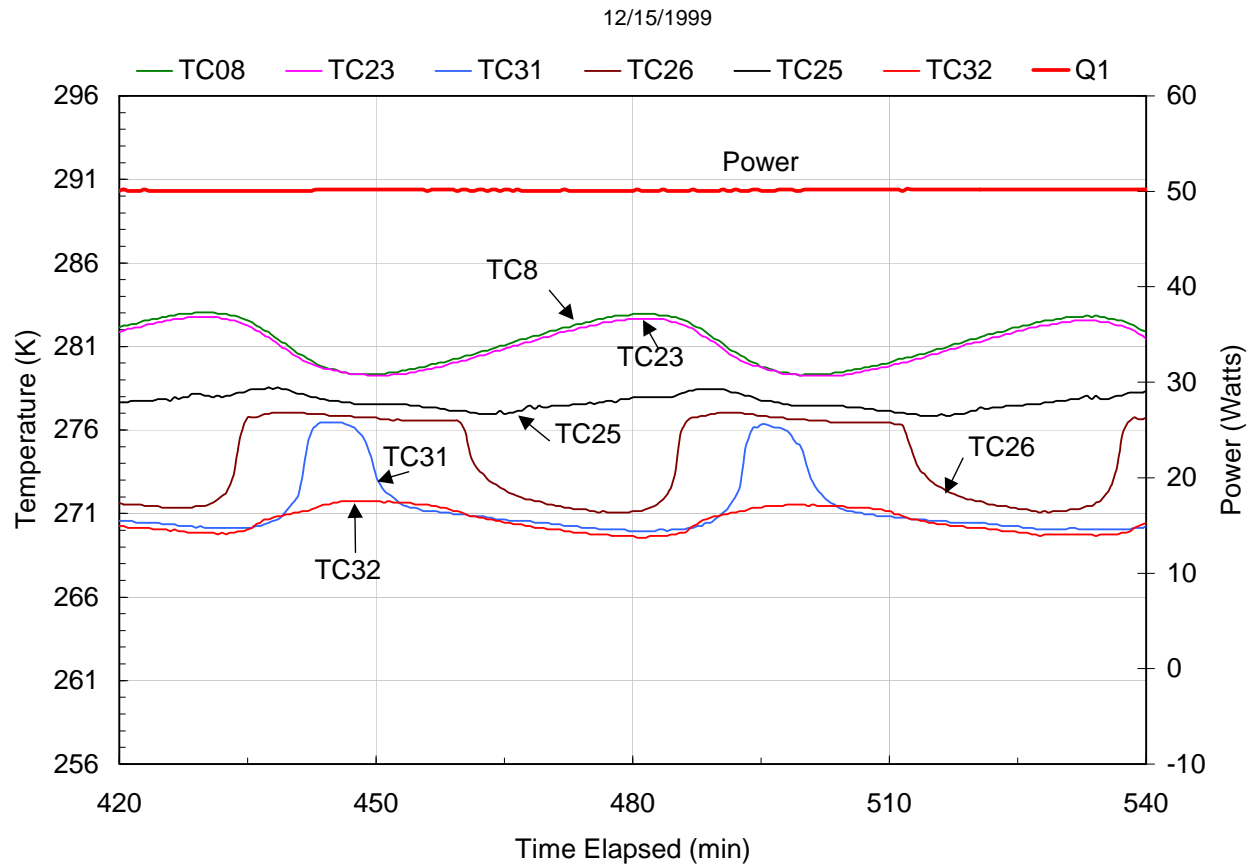
- No temperature oscillation when the sink temperature is higher than ambient temperature.
- At low sink temperature, lower power lead to higher amplitude and longer period of temperature oscillation.

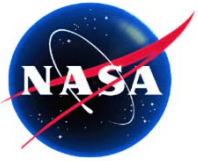




Temperature Oscillation in TES LHP EDU (50W/268K)

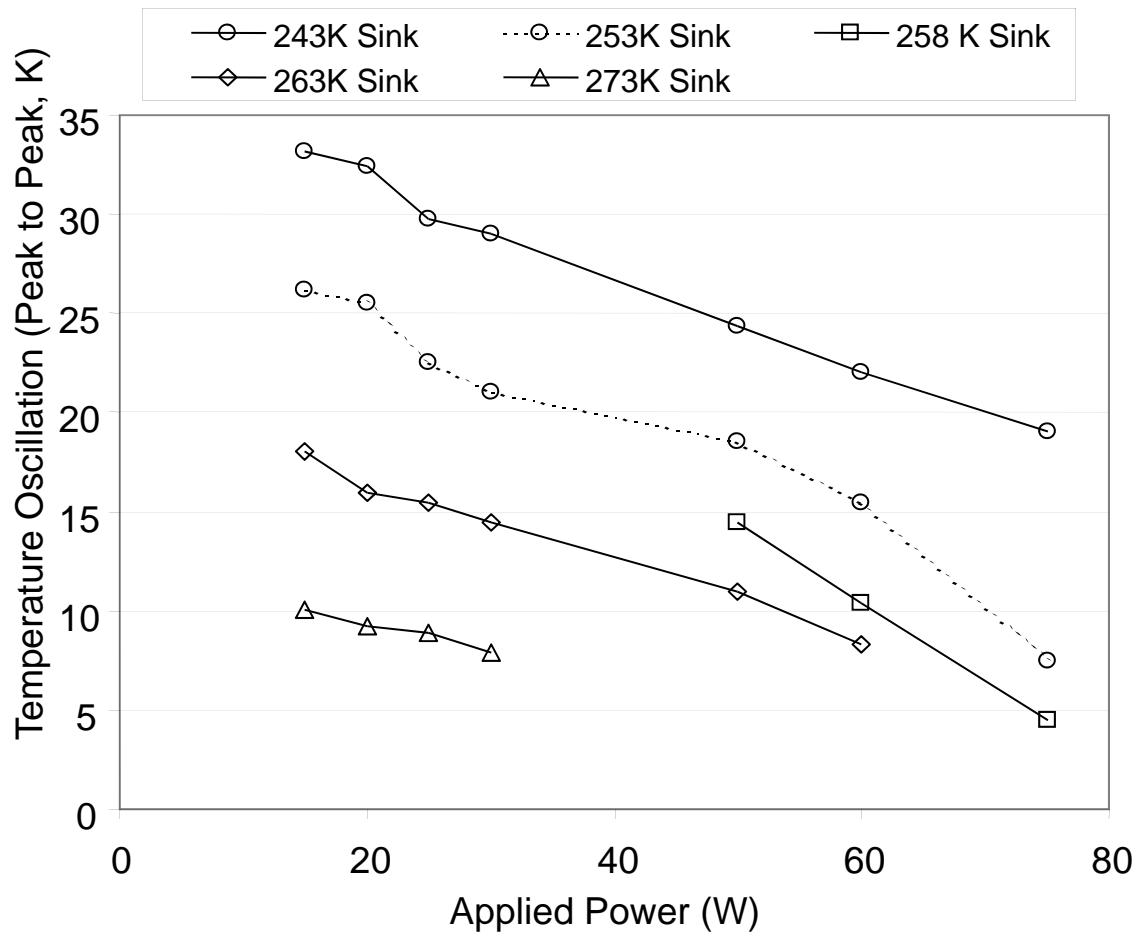
- A relatively high power and a high sink temperature lead to a smaller amplitude and a shorter period of temperature oscillation.
- The periods for temperature rise and fall become less asymmetric.

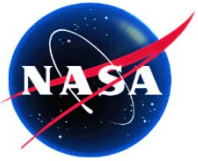




Amplitude of Temperature Oscillation vs Applied Power and Sink Temperature

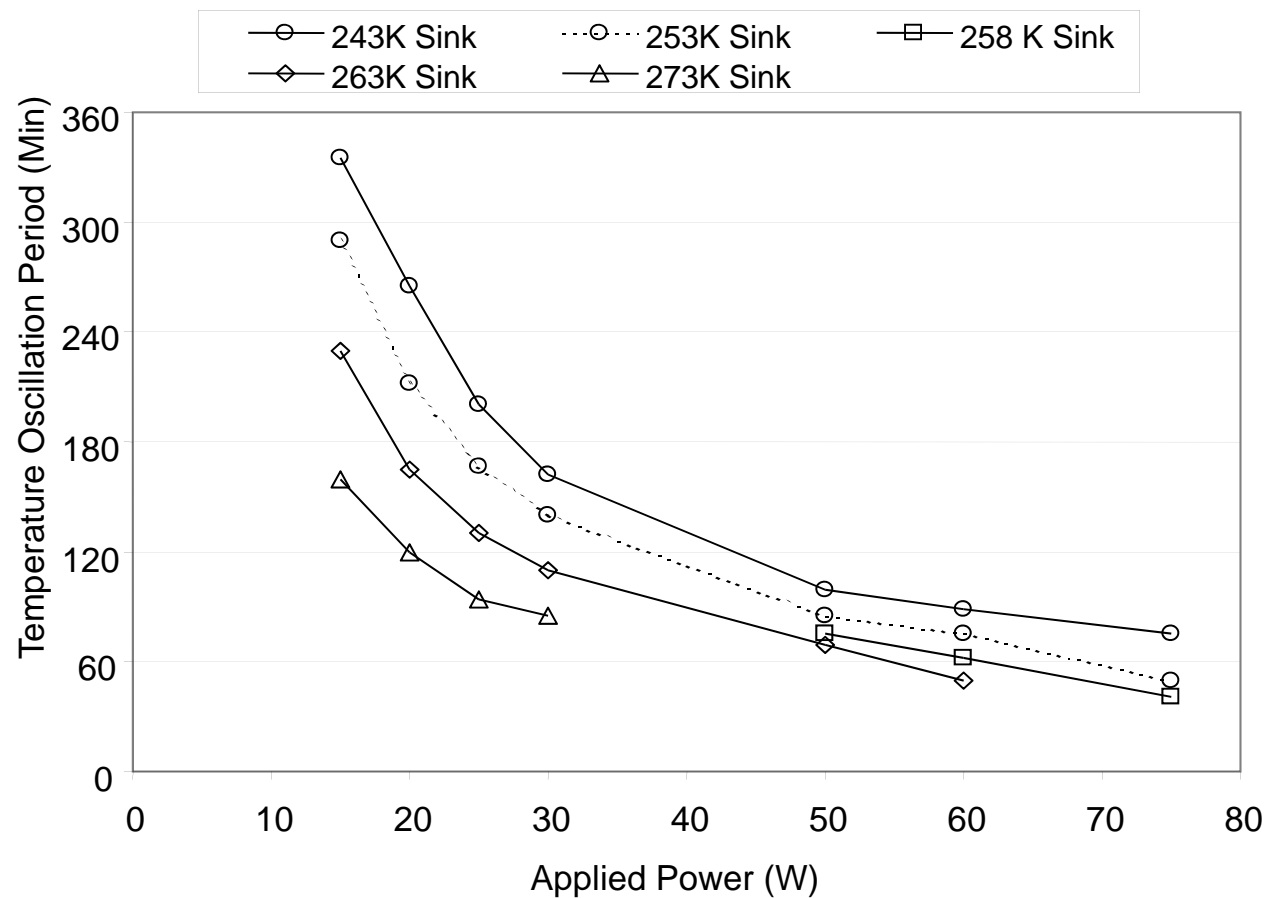
- The amplitude of temperature oscillation increases with:
 - a decreasing power
 - a decreasing sink temperature

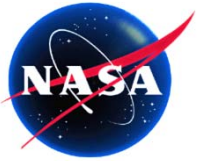




Period of Temperature Oscillation vs Applied Power and Sink Temperature

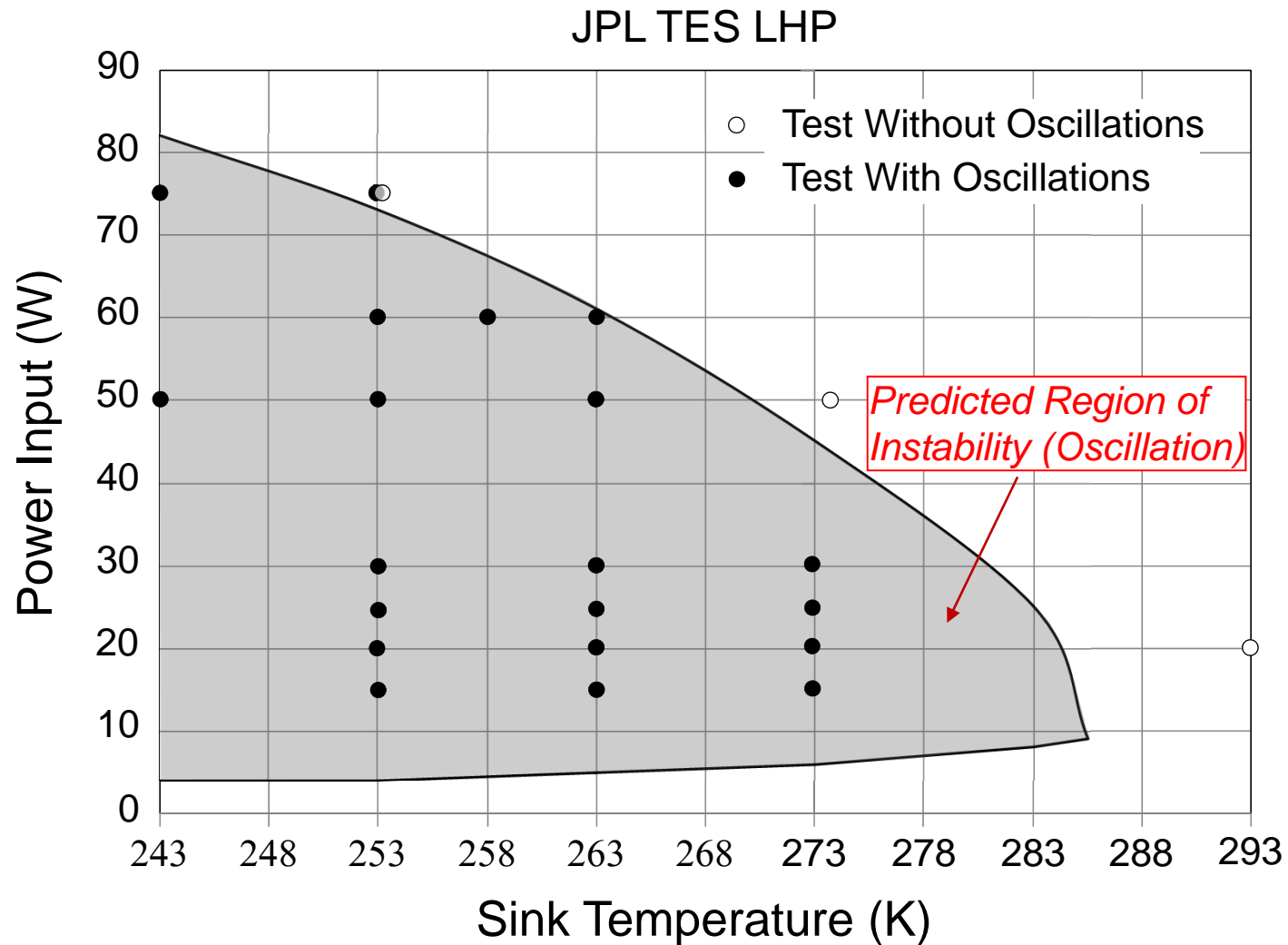
- The period of temperature oscillation increases with:
 - a decreasing power
 - a decreasing sink temperature

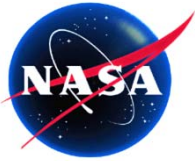




Prediction of LHP Temperature Oscillations

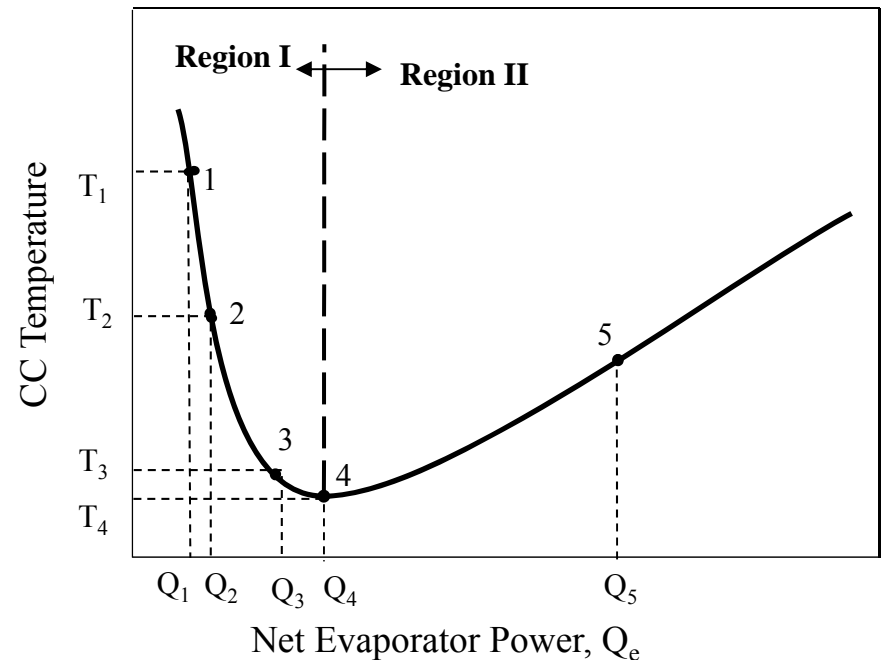
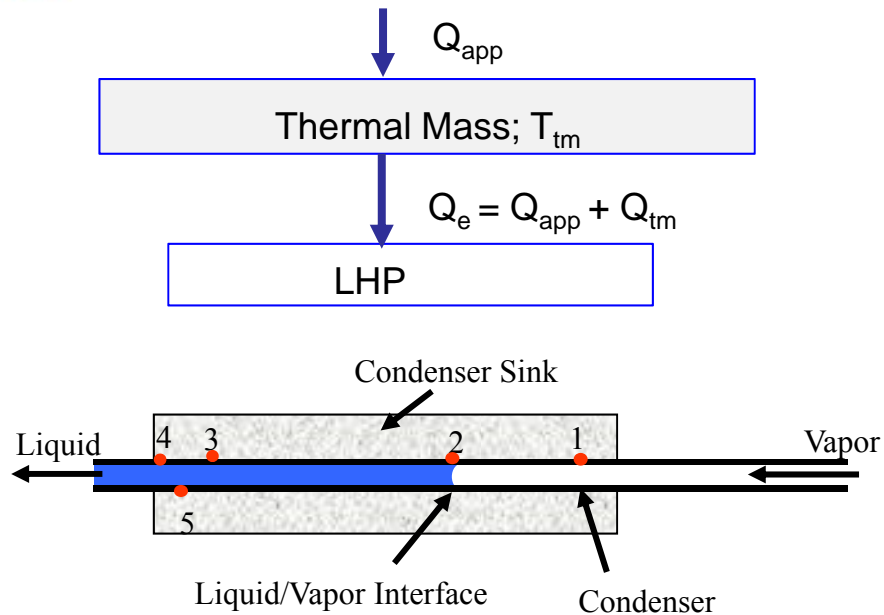
Analytical Predictions versus Test Data (Hoang & Baldauff)



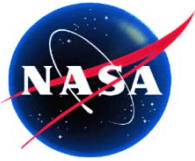


Heat Load Modulation by Thermal Mass

LHP Operates in Region II

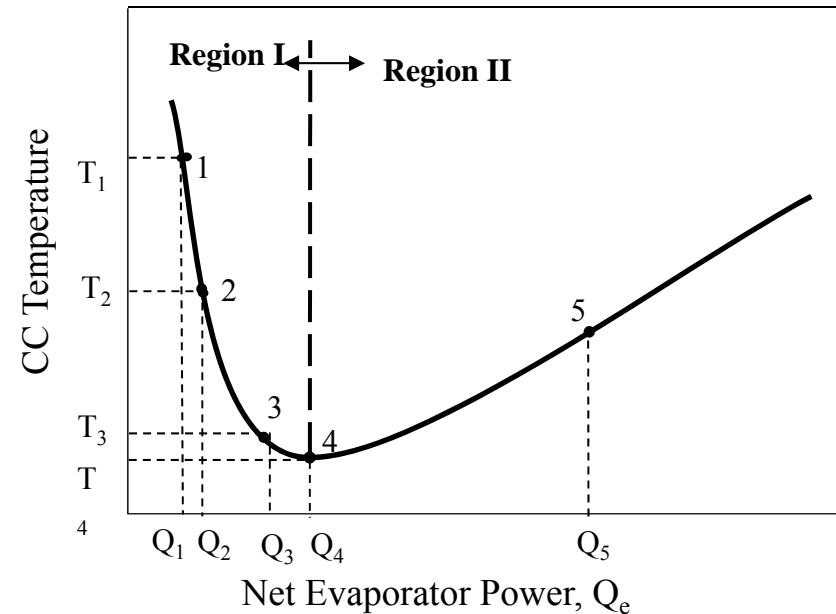
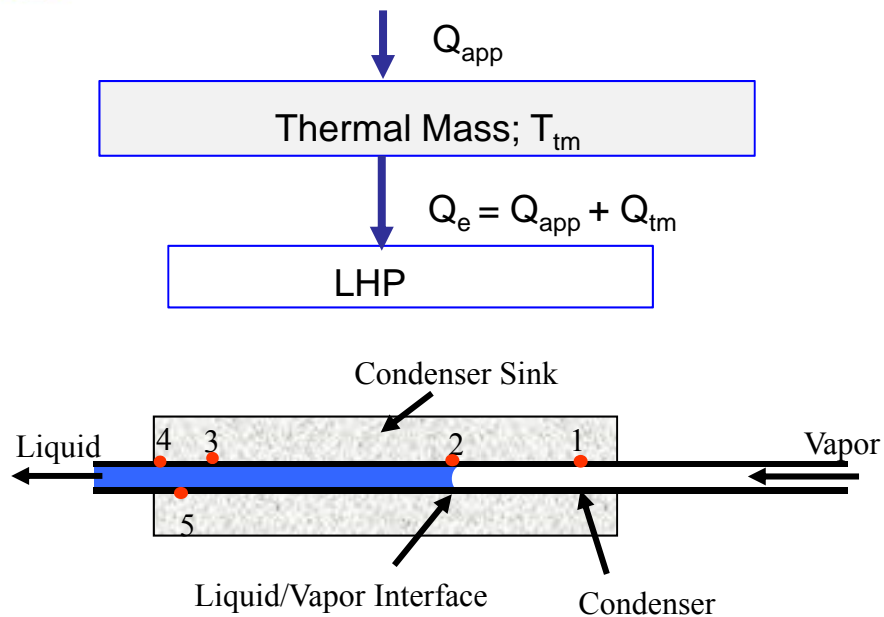


- When a heat load of $Q_{app} = Q_5 > Q_4$ is applied to the evaporator, the LHP operate in Region II. Under steady state, the vapor front will stay stably at location 5 inside the condenser and $T_{cc} = T_5$.
- No high frequency low amplitude or low frequency high amplitude temperature oscillation will occur with or without a large TM attached.
 - Without a large TM, the transient period will be short
 - With a large TM, the transient period will be longer.

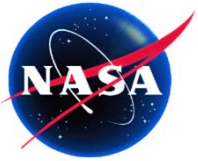


Heat Load Modulation by Thermal Mass

Vapor Front Near Condenser Exit

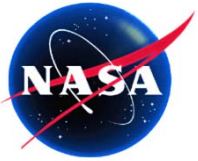


- When a heat load of $Q_{app} = Q_4$ is applied to the evaporator and T_{cc} is near T_4 , the vapor front will be near location 4 in the condenser.
- Without a large TM attached to the evaporator, high frequency low amplitude temperature oscillations will occur.
- If a large TM is attached to evaporator, the behavior will be similar to high frequency low amplitude temperature oscillations except that the frequency will be lower (period is longer) and the amplitude will be slightly higher.
 - Heat load modulation by TM is limited, i.e. $\pm Q_{tm}$ will be small and the vapor front cannot move far from location 4. Low frequency high amplitude temperature oscillation will not occur.



Summary and Conclusions (1/2)

- **The LHP natural operating temperature (non-controlled CC) is well defined with a constant evaporator power and a constant sink temperature.**
- **Under certain conditions, the CC temperature never reaches a true steady state, and display oscillatory behaviors.**
- **Two types of temperature oscillations are of concern for spacecraft applications.**
 - **High frequency low amplitude temperature oscillation**
 - **Low frequency high amplitude temperature oscillation**
- **High frequency low amplitude temperature oscillation can occur under the following conditions:**
 - **The LHP operating temperature coincide with its lowest natural operating temperature. The LHP may or may not have a large thermal mass attached to its evaporator.**
 - **The LHP has a very low heat load and the vapor front is near the condenser inlet. No large thermal mass is attached to its evaporator.**



Summary and Conclusions (2/2)

- **Low frequency high amplitude temperature oscillation can occur when the LHP operates under the variable conductance mode and all of the following three necessary conditions are satisfied:**
 - A large thermal mass is attached to the evaporator.
 - A small power is applied to the thermal mass.
 - The condenser has a cold sink (colder than the surrounding temperature)
- **This presentation provides detailed explanations on the underlying physical processes of these types of temperature oscillation.**
 - Interactions among LHP components and its environment
- **Analytical models exist to predict when these types of temperature oscillation will occur.**
 - Heat load, sink temperature, ambient temperature, thermal mass attached to LHP evaporator
- **Both types of temperature oscillation disappear when the CC temperature is actively controlled through cold biasing.**